TECHNICAL ASPECTS OF DETECTION AND INSPECTION CONTROLS OF A NUCLEAR WEAPONS TEST BAN

APPENDIXES TO

HEARINGS

BEFORE THE

SPECIAL SUBCOMMITTEE ON RADIATION

AND THE

SUBCOMMITTEE ON RESEARCH AND DEVELOPMENT

OF THE

JOINT COMMITTEE ON ATOMIC ENERGY

CONGRESS OF THE UNITED STATES

EIGHTY-SIXTH CONGRESS

SECOND SESSION

ON

TECHNICAL ASPECTS OF DETECTION AND INSPECTION CONTROLS OF A NUCLEAR WEAPONS TEST BAN

PART 2 OF 2 PARTS

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APPENDIXES

APPENDIX 1

REPORT OF THE CONFERENCE OF EXPERTS TO STUDY THE METHODS OF DETECTING VIOLATIONS OF A POSSIBLE AGREEMENT ON THE SUSPENSION OF NUCLEAR TESTS

I. INTRODUCTION

A. In accordance with an agreement reached as a result of an exchange of letters between the Chairman of the Council of Ministers of the Union of Soviet Socialist Republics, N. S. Khrushchev, and the President of the United States of America, Dwight D. Eisenhower, regarding the calling of a conference of experts to study the possibility of detecting violations of a possible agreement on the suspension of nuclear tests, there began on 1 July 1958, in Geneva, in the Palais des Nations, a conference of, on the one hand, experts from Western countries and, on the other hand, delegations of experts of the Union of Soviet Socialist Republics, the Polish People's Republic, the Czechoslovak Republic and the People's Republic of Romania.

B. The Secretary-General of the United Nations was represented at the Conference by his Personal Representative, Mr. T. G. Narayanan. Conference facilities and Secretariat services were provided by the United Nations. The Experts express their appreciation for the good offices of the Secretary-General and his Personal Representative, and for the services of the Secretariat staff attached to the Conference.

C. The agenda for the Conference, adopted on 4 July, included the following main questions:

1. Exchange of opinions on the problem of the various methods for detecting atomic explosions and on other general problems of the Conference deliberations.

2. Determination of a list of basic methods of systematic observations for phenomena indicative of an explosion.

3. A system for controlling the observance of an agreement on the cessation of nuclear tests.

4. Drawing up a report of experts to the governments of those countries represented at the Conference, with conclusions and suggestions regarding a system for controlling the observance of an agreement on the cessation of nuclear tests.

D. The Conference held 30 official sessions and completed its work on 21 August 1958. By prior agreement the Conference held its sessions in private.

E. The Conference of Experts considered the phenomena accompanying nuclear explosions set off under various conditions.

F. Some of these phenomena, namely the acoustic waves occurring when there are explosions in air and in water, the seismic oscillations that occur when there are explosions on the ground, under the ground, and under water, the radio pulses that are produced when there are explosions in the atmosphere, and the optical and gamma radiation when propagated over long distances, serve to indicate explosions and to estimate their time and place.

G. When nuclear explosions occur in the atmosphere the radioactive debris which is formed mixes in the atmosphere, and is dispersed over great distances. If a nuclear explosion is set off in the ocean or in the earth's crust, the radioactive debris will remain concentrated close to the site of the explosion for a considerable time.

H. The sensitivity of modern physical, chemical and geophysical methods of measurement makes it possible to detect nuclear explosions by the indications described above at considerable distances, as hereafter described. Thus it is known that explosions of high yield which are set off on the surface of the earth and in the lower part of the atmosphere can be detected without difficulty at points of the globe which are very remote from the site of the explosion. On the other hand, explosions which are of low yield (a few kilotons) can be detected with good reliability given the present state of observational techniques only if there is a specially set up control system such as that suggested in Section IV of this report.

I. A basic difficulty in detecting and identifying small explosions arises because many natural phenomena (earthquakes, thunder storms and others) give signals which are similar to those produced by explosions, or which by their presence hinder the detection of the signals sought.

J. The discrimination of the signals of natural events from signals of explosions is aided by a careful analysis of the recorded data, taking into account readings obtained at several points. Those remaining unidentified events which could be suspected as being nuclear explosions might be resolved by inspection of the site.

K. The Conference of Experts has considered the methods of detecting nuclear explosions by the acoustic, hydroacoustic and seismic oscillations which they produce in the air, water, or in the earth's crust, and, also the detection of explosions by the electromagnetic oscillations which are propagated from them, and by the radioactive debris that the explosions cause.

L. The Conference has examined the effectiveness and limitations of each of these methods for the detection of nuclear explosions and it has agreed that the combined use of the various methods considerably facilitates the detection and identification of nuclear explosions.

M. After examining the separate methods, the Conference examined the question of the technical equipment of the control system necessary to detect and identify nuclear explosions, and, after that, it passed to the question of the control system as a whole.

N. As a result of the examination of these questions the Conference reached the conclusion that it is technically feasible to set up, with the capabilities and limitations indicated in Section IV of this report, a workable and effective control system for the detection of violations of an agreement on the worldwide cessation of nuclear weapons tests.

O. In the present report information is given about the various methods of detection and identification of nuclear explosions, about the technical equipment of a control system and about a control system as a whole. Copies of the individual documents containing the conclusions adopted by the Conference on each of the questions mentioned are attached to the present report. Verbatim records and working documents in the working languages of the Conference will follow as soon as they are available for attachment to the report.

II. BASIC METHODS FOR DETECTION AND IDENTIFICATION OF NUCLEAR EXPLOSIONS

A. Conclusions as to the applicability of the Method of Recording Acoustic Waves for the Detection of Nuclear Explosions.

The Conference of Experts examined the process of propagation of the acoustic waves caused by nuclear explosions and the methods of recording these waves with the aim of determining the possibility of using them for detecting nuclear explosions.

1. When there are explosions in air, a strong air acoustic wave is formed which propagates over large distances. An indication of the amplitude of the air pressure wave is given by a formula which is approximately valid for a homogeneous atmosphere and according to which this amplitude is proportional to the cube root of the yield and inversely proportional to the distance. However, the amplitude of this acoustic wave is strongly dependent upon meteorological conditions and cannot be predicted accurately by a simple formula of such a kind. The observed amplitude in certain cases can be five times larger or smaller than that predicted by a formulation which includes only the energy release and the distance to detecting station.

2. Existing apparatus of special design can detect the air wave from a one kiloton explosion in the air above local background noise at relatively large distances.

The detection capability of a single station is strongly dependent upon the orientation of the propagation path to the station with respect to the upper winds. When the upper winds are mainly in one direction, a one kiloton explosion can be detected with a high degree of confidence downwind at a distance of 2,000 to 3,000 kilometres and upwind at a distance of 500 kilometres. When the upper winds are erratic and the average wind is small, such as frequently happens in the spring and fall, detection of a one kiloton explosion can be accomplished with a similar degree of confidence to a distance of approximately 1,300 kilometres independently of the direction. On the basis of the records from three stations, the location of the explosion can be determined with an accuracy of better than 100 kilometres.

3. The acoustic apparatus at control posts at the above distances from an explosion can detect explosions which occur between the surface and a height of 30 kilometres. A reasonable extrapolation of existing experience indicates that

for explosions taking place up to an altitude of about 50 kilometres there should not be a great change in the detectability of the acoustic wave. Whether a substantial acoustic wave will be generated at higher altitudes is not well known from direct experiment or from any theoretical considerations so far discussed. Deep underground and underwater explosions do not produce air waves sufficiently intense for detection purposes.

An underwater explosion in the oceans generates very strong underwater sound waves (hydroacoustic), which even in the case of small explosions can be detected at distances of about 10,000 kilometres.

4. Acoustic waves which resemble in certain cases the acoustic signals of nuclear explosions may be produced by natural events (primarily meteoric, volcanic or submarine disturbances). In such cases the identification of the event as natural or as a nuclear explosion must be based on a comparison of acoustic data with those obtained by aid of other methods.

5. It is noted that methods of recording of pressure waves may be further improved to increase the precision and the sensitivity, and to eliminate background noise and spurious signals.

B. Conclusions as to the Applicability of the Method of Using Radioactive Debris for Detecting and Subsequently Identifying Nuclear Explosions.

The Conference of Experts has studied the process of the dissemination of radioactive debris resulting from a nuclear explosion and has considered the collection of samples of radioactive debris and its analysis as one of the methods for detecting and subsequently identifying nuclear explosions.

1. When an explosion occurs a considerable quantity of radioactive debris is produced. If the explosion is based on a fission reaction then this quantity amounts to 3×10^8 curies per 1 kt TNT equivalent of the energy of the explosion as of one hour after the reaction. Thermonuclear reactions will lead to the formation of Carbon 14, Tritium, and other radioactive substances which result from neutron irradiation and which, in principle, can also be used to detect an explosion.

2. When nuclear explosions occur between the earth's surface and a height of approximately ten kilometres the radioactive debris is thrown into the atmosphere where it is carried by winds to great distances. The concentration of this radioactive debris is greatly influenced by the vertical and horizontal distribution

of the wind in the troposphere and in the lower layers of the stratosphere. The concentration is also decreased as a consequence of washing out by rain and gravitational deposition.

3. The distribution by height of the radioactive debris carried in the atmosphere will depend in the first place on the energy of the explosion, on the conditions in which the explosion took place (i.e. on the earth, under the earth, or in the air) and on the meteorological conditions at the moment of explosion. In the case of low energy explosions in the air up to a height of approximately ten kilometres the radioactive debris will initially concentrate in a small volume below the tropopause. This debris will gradually get disseminated both horizontally and vertically in the troposphere and in the course of a period of from one to thirty days (depending on the turbulence of the atmosphere, the wind structure, and the dimensions of the particles which carry the radioactive substances) it can be detected close to the earth's surface, as also at various heights up to the tropopause.

4. The spreading of the cloud in the atmosphere is determined by many meteorological processes. As a result of the action of these processes the cloud is bound to reach a stage when it is mixed in a vertical direction and spread in a horizontal direction in such a way as to afford the most convenient conditions for taking samples.

Calculations and experimental data give ground for considering that this stage will be reached in the period between the fifth and twentieth day of the existence of the cloud. Before that period the cloud may be too small, both in its horizontal and its vertical extent. After thirty days have expired a considerable part of the radioactive debris will decay and a sample will constitute a lesser proportion of the natural or other background, thereby making more difficult the detection and identification of an explosion.

5. Existing radiochemical techniques make it possible to detect and identify fresh decay products in a sample of radioactive debris containing about 10^8 fissions. The time of origin of this fresh debris can be determined within five to ten per cent of its age if the sample contains about 10^{10} fissions and is not contaminated to any considerable extent by old fission products.

6. The taking of samples on the surface of the earth by a network of control posts makes it possible to carry out continual monitoring of the contamination of the air at many separate points by means of air filtration and also by collecting

radioactive fallout and fallout in rain. If control posts are disposed at distances of the order of 2,000 - 3,000 kilometres thon an explosion with an energy of 1 kt set off in the troposphere (0 - 10 kilometres above the surface of the earth) will be detected with a high degree of reliability in the period of five to twenty days although the place of explosion cannot be exactly determined and although the time of explosion will be determined with some error. Calculation shows that with favourable meteorological conditions an explosion of even lesser energy can be detected in this way.

In the course of the period of time of from two to five days after an explosion of energy equivalent to 1 kt the collection of a sample of radioactive debris from the explosion which is suitable for analysis can be effected in the air by an aircraft if the area of the supposed location of the cloud is known approximately. The taking of such a sample will make it possible to establish approximately the point of the explosion by means of using meteorological data for back-tracking the trajectory of movement of the cloud.

7. Underground or underwater explosions set off at shallow depths and accompanied by the throwing up of earth or water can also be identified by the method of collecting radioactive samples although with lesser reliability than for explosions of the same energy in the troposphere.

8. The Conference of Experts considers that systematic measurements of radioactive substances in the air and also the collection of radioactive aerosols deposited on the ground and measurements of the radioactivity of precipitation can be successfully used for the detection of nuclear explosions and also, in many cases, for assessing certain parameters relating to them even in the absence of other indications.

The utilisation for a regular control service, as a method for detecting nuclear explosions, of the taking of samples of the air by aircraft over oceans can be used for detecting nuclear explosions. For this purpose use should be made of existing aircraft flights over the oceans which are carried out by various countries for the purposes of meteorological observations.

9. The Conference of Experts considers that the method of taking samples of radioactive debris can also be used successfully for subsequent investigation of the fact of a nuclear explosion in those cases when there are the appropriate indications from other methods.

For this purpose it is possible to use the detection of radioactive debris remaining at the point of the supposed explosion (on the earth's surface, under the earth, in the water) and also the determination of the presence of a radioactive cloud in the period between two and five days after a supposed explosion in the atmosphere in the area where the cloud is calculated to be by the time of investigation.

In such a case search for the radioactive cloud can be made on an aircraft having equipment for the taking of a sample of radioactive debris. To this end use should be made chiefly of the aircraft flights over the oceans made for the purposes of meteorological observations.

10. In some cases use can be made of aircraft flights over the territories of the USA, the USSR, the UK and other countries to collect air samples for the purpose of checking on data obtained by other methods of detection of nuclear explosions.

The Experts consider that to accomplish this task it would be quite sufficient to make use of the aircraft of the country being overflown and that in such cases it is sufficient that flights for the purpose specified should be made along routes laid down in advance. Representatives of the USSR, the USA, the UK or other States participating in the operation of the control system may be on board these aircraft in the capacity of observers.

11. The experts note that in the course of time the sensitivity and efficiency of the method of collecting radioactive debris will increase as a consequence of the atmosphere becoming cleared of the radioactive products it contains, and also as a result of the perfection of the techniques for collecting and analysing samples.

C. Conclusions as to the Applicability of the Method of Recording Seismic Waves for the Detection of Nuclear Explosions.

The Conference has considered the processes of propagation of seismic waves generated by nuclear explosions and the methods for recording these waves for the purpose of determining the possibility of using them for the detection of underground and underwater nuclear explosions.

1. When nuclear explosions occur under the ground or under the water, longitudinal, transverse and surface waves are formed and get propagated to great distances. The first longitudinal wave is the most important, both for detecting an explosion and for determining the place of the explosion, and also for distinguishing an earthquake from explosions. Transverse and surface waves also help to define the nature of a seismic perturbation.

2. Longitudinal seismic waves caused by underground nuclear explosions set off under conditions analogous to those in which the Rainier* shot occurred can be detected and the direction of first motion of the longitudinal wave can be determined at a distance of approximately 1,000 kilometres, and also at distances of approximately 2,000-3,500 kilometres at sites which are considerably more quiet than the average for:

(a) explosions of the order of one kiloton recorded during periods of favourable noise conditions

(b) explosions of the order of five kilotons recorded during periods of unfavourable noise conditions.

It must be noted that all seismic stations situated at thousands of kilometres from one another cannot have an identically high or identically low level of background at one and the same time.

3. Conditions for detection and identification of underwater explosions set off in shallow water but at a sufficient depth, are considerably more favourable than conditions for detecting underground explosions.

4. Control posts carrying out seismic observations should be put at sites with a minimal level of microseismic background, such as are possible in internal continental regions. Such stations, when provided with arrays of seismographs, can

* The underground nuclear explosion "Rainier" with an energy of 1.7 kilotons (Nevada) was set off in unfavourable conditions for transferring energy to the ground. However, even worse conditions of coupling are possible.

insure the obtaining of the data indicated above. However, at stations which are in unfavourable regions such as coastal and island regions the noise level will be higher than at quiet stations inside continents. In these cases for detection and determination of the sign of first motion the energy of the explosion must increase in the ratio of the power of 3/2 with respect to the increase of background level. This is in part compensated by the fact that quiet stations inside continents will register more powerful explosions at distances of from 2,000 to 3,500 kilometres. Bursts with an energy of 5 kilotons and more will be detected by quiet stations placed at the distances named.

5. The majority of earthquakes can be distinguished from explosions with a high degree of reliability if the direction of first motion of the longitudinal wave is clearly registered at 5 or more seismic stations on various bearings from the epicentre. Thus not less than 90 per cent of all earthquakes taking place in continents can be identified. The remaining 10 per cent or less of cases will require the analysis of additional seismograms where this is possible; and for this purpose use must also be made of the data of the existing network of seismic stations. If required, these supplementary stations should be further equipped with improved apparatus. In relatively aseismic areas it is sufficient merely to define the position of the epicentre. In this connection cases of detection of seismic events will be regarded as suspicious and will require further investigation with the help of other methods. For these cases which remain unidentified inspection of the region will be necessary.

In regions where the regular disposition of seismic stations in quiet conditions is not possible, the percentage of correct identification of earthquakes will be less.

With modern methods and making use of the data of several surrounding seismic stations the area within which an epicentre is localized can be assessed as approximately 100-200 square kilometres.

6. It is noted that the range and accuracy of recording and identifying underground nuclear explosions can be improved in the future by means of perfecting the methods of recording seismic waves, both by way of perfecting apparatus and also by way of perfecting the methods for differ tiating an earthquake from explosions.

D. Conclusions on the Applicability of the Method of Recording of Radio Signals for the Detection of Nuclear Explosions.

The Conference of Experts considered the generation and propagation of radio pulses originating from a nuclear explosion and the methods of recording these signals in order to determine the possibility of using them for the detection of nuclear explosions.

1. In the case of a nuclear explosion in the atmosphere, there arises a powerful electromagnetic radiation (radio signal), caused by the gamma radiation accompanying the explosion. In the case of underground, underwater, or specially shielded explosions radio emissions are not expected which can be recorded at great distances by modern techniques.

When the explosion is carried out on or above the surface of the earth (water) and without specially constructed layers to absorb gamma rays, the energy and spectral distribution of the radio signal are such that its essential components are propagated over the whole terrestrial globe. The strength of the radio signal depends upon certain features of the construction of the bomb and on the altitude of the explosion. An explosion of 1 kiloton yield can be detected by means of radio signals at distances exceeding 6,000 km assuming that in the neighbourhood of the receiving station there is no high noise level from local thunderstorms or other sources.

By radio direction finding methods, it is possible to determine the azimuth of the signal source with an accuracy of about 2°, i.e., about 30 km at a distance of 1,000 km. The time of production of the signal may be established with an accuracy of several milliseconds. The attainment of such accuracy depends on the choice of sufficiently flat location and on the absence of electrical interference at the receiving site.

2. Lightning flashes emit radio signals in the same frequency range and act as interference for the method of detection of a nuclear explosion by means of its radio signal.

Close to the source of radiation, the forms of radio signals from lightning and from nuclear explosions examined to date are quite different. However, at distances exceeding 1,000 kilometres, due to the distortion of the form of radio signals in the wave guide formed by the earth and the ionosphere, the form of radio signals from some individual lightning flashes is similar to the signal from nuclear

explosions. The number of signals from lightning flashes recorded by apparatus without using special techniques of signal selection depends on the sensitivity of the apparatus and on the locality and can amount to from ten to several hundred signals per second. Existing techniques can be applied to exclude automatically the preponderant majority of signals from lightning. The distinction of the remaining signals due to atmospherics from those due to nuclear explosions requires the application of special methods of discrimination, including criteria on form of signal, spectral distribution and distance to source of radiation.

In the present state of the technique of the discrimination of signals in some individual cases the record of a signal cannot be identified either as coming from a nuclear explosion or from lightning.

3. The Conference of Experts recommends that further research should be carried out in order to understand more fully the physical properties of atmospherics involved in differentiating signals from nuclear explosions and atmospherics, by means of the development of the theory of this problem, the collection and systematization of data about atmospherics and the development of suitable automatic instruments. The Conference considers that there are good prospects for improvement of procedures of signal discrimination.

4. Theoretical considerations suggest that recording of radio signals can be used to detect nuclear explosions occurring at altitudes up to the order of 1,000 kilometres.

E. Conclusions on the Methods of Detection of Nuclear Explosions Carried out at High Altitude (More than 30 to 50 Kilometres) Above the Earth

The Conference of Experts has given theoretical consideration to the gamma radiation and neutrons resulting from a nuclear explosion and the conditions of recording them from earth satellites; and to optical phenomena and ionization of the air in the upper layers of the atmosphere in the case of a high altitude explosion (altitudes above 30-50 kilometres) and has arrived at the following conclusions:

1. A kiloton nuclear explosion produces at its source delayed gamma-rays from fission products, and prompt gamma-rays and neutrons. The number of prompt gamma-rays and neutrons depends upon the construction of the device and upon the materials surrounding it. The delayed gamma-rays are insignificantly affected by these factors. At a distance of 10^4 kilometres in vacuo, typical quantities of radiation from a one kiloton fission explosion are:

(a) Delayed gamma-rays

10^4 quanta/cm^2 during the first second

(b) prompt gamma rays*

10^2 quanta/cm^2

distributed over a time of about 10^{-7} sec.

(c) Neutrons

10^4 neutrons/cm^2

distributed over a time of a few seconds.

The cosmic background at the height at which earth satellites orbit is under study at the present time, attention being paid to the quantity, nature and energy of the particles; however, on the basis of preliminary data, it can be considered that the detection of an explosion from an earth satellite is possible, by means of registering the gamma-rays accompanying the nuclear reaction, neglecting shielding, and also by means of registering the gamma rays of the fission products and the neutrons. If both prompt gamma rays and neutrons are registered, it is possible to get some idea of the distance to the explosion. The use of gamma-rays from a nuclear explosion will make it possible to detect the explosion in cosmic space at a distance of the order of hundreds of thousands of kilometres from the earth. Estimate of the maximum distance for the detection requires data concerning the magnitude of the cosmic radiation at the orbit of the earth satellite. If there is an explosion at a height of 30-50 km and above, and if the height at which the earth satellite orbits is some thousands of kilometres, one can neglect the absorption of gamma quanta in the upper layers of the atmosphere. The Conference of Experts considers that it is possible to use for the detection of nuclear explosions at high altitudes the registration of gamma-radiation and neutrons with properly instrumented earth satellites.

2. In the case of an explosion at a great height light will be emitted at the point of the explosion and there will be luminescence in the upper layers of the atmosphere under the action of X-rays and fast atoms from the materials in the device. Light phenomena may be detectable from the surface of the earth in clear weather at night with the help of simple apparatus; in day time with the help of

* Special shielding of the exploding device can considerably reduce the gamma-radiation accompanying the reaction, but cannot reduce the radiation from fission products. However, such shielding involves increasing by several times the weight of the whole device.

more sensitive apparatus. In cloudy weather the detection of optical phenomena from stations on the earth's surface would probably be extremely difficult.

The radiation from a nuclear explosion creates in the upper layers of the atmosphere a region of increased ionization which is detectable by the absorption of cosmic radio-signals or by anomalies in the propagation of radio waves.

Our knowledge of the absorption of cosmic noise by ionospheric phenomena is not sufficient to determine the number of natural events similar to those resulting from a nuclear explosion.

The Conference of Experts considers that it is possible to use the recording of ionospheric phenomena, using appropriate radio techniques, and of optical phenomena for the detection of nuclear explosions at high altitudes.

3. The Conference of Experts has not considered the problem of the detection of nuclear explosions which might be conducted in cosmic space at distances of millions of kilometres from the earth.

F. The Conference has recommended the inclusion of the first four of these methods in the number of basic methods for detecting nuclear explosions by means of a network of control posts, and considers it possible to use several methods for detection of nuclear explosions at high altitudes as stated in IIE1 and IIE2.

III. CONCLUSIONS ON THE QUESTION OF THE TECHNICAL EQUIPMENT OF THE CONTROL SYSTEM FOR THE DETECTION AND IDENTIFICATION OF NUCLEAR EXPLOSIONS

The Conference of Experts has considered the questions related to the technical equipment of a control net intended to detect and identify nuclear explosions, and has come to the following conclusions:

1. The posts of the control net situated in continents should regularly be equipped with apparatus for the detection of explosions by the acoustic and seismic methods and also by the methods of recording radio signals and of collecting radioactive debris.

2. Certain posts situated on islands or near the shores of oceans should be equipped, in addition to the methods just mentioned, with apparatus for hydroacoustic detection of explosions.

3. Posts located on ships stationed or drifting within specified ocean areas should be equipped with apparatus for the detection of explosions by the method of collecting radioactive debris and by the hydroacoustic method. The method of recording radio signals and the acoustic method might also be used on ships if suitable equipment is developed, but the effectiveness of these two methods, particularly the acoustic one, will be considerably less than on land.

4. The apparatus installed at posts of the control network must be uniform and must satisfy the following basic technical requirements:

A. Seismic apparatus

The seismic apparatus of the control post should include:

(1) Approximately 10 short-period vertical seismographs dispersed over a distance of 1.5-3 kilometres and connected to the recording system by lines of cable. The seismographs should have a maximum magnification of the order of 10^6 at a frequency of 1 c.p.s. and a receiving band adequate to reproduce the characteristic form of the seismic signal;

(2) 2 horizontal seismographs with the parameters indicated in point (1);

(3) One three-component installation of long-period seismographs having a broad receiving band and a constant magnification of the order of $10^3 - 2 \times 10^3$ in the period range 1 - 10 seconds;

(4) One three-component installation of seismographs with a narrow receiving band and magnification of the order of 3×10^4 when T = 2 - 2.5 seconds;

(5) At certain posts one three-component installation of long-period seismographs with magnification of the order of $10^4 - 2 \times 10^4$ at periods of T = 25 seconds;

(6) Auxiliary equipment necessary in order to get precise records of the seismic signal; recording devices, chronometers, power supply units and apparatus for receiving automatic radio-signals giving correct time.

The seismic apparatus should be installed in places with a minimal level of micro-seismic background, away from industrial areas, and on outcrops of bedrock (where possible). The seismographs should be installed in suitable vaults.

The area required for installing the seismic apparatus should be about 3 x 3 kilometres.

B. Acoustic apparatus

(1) The infra-acoustic equipment for a control post should include not less than three sets of microbarographic units each of which should have: a system for averaging out turbulent noise, a pressure sensing unit, a transmission line and appropriate electronic amplifiers and automatic writing instruments;

(2) The sensitivity of the microbarographic stations must ensure recording of acoustic signals in the period range 0.5 - 40 seconds, with an amplitude of 0.1 dynes per cm^2;

(3) The pressure sensing units of the microbarographs should be dispersed at about 10 kilometres from one another in order to determine the direction of arrival of the acoustic signal and the speed of propagation of the signal;

(4) The hydroacoustic apparatus for a post, which is recommended for use only in oceanic zones, should include several hydrophones placed in the main submarine sound channel.

The hydrophones should be connected with the recording station on the coast by cables. Recordings of the hydroacoustic signal should be made in several frequency sub-ranges, covering a general frequency range of from one cycle per second to several thousand cycles per second.

The infra-acoustic equipment operates best in areas of low surface winds and flat terrain covered with trees or shrubs.

C. Apparatus for recording a radio signal

The apparatus for recording a radio signal should consist of:

(1) A loop-shaped radio direction finder or a radio direction finder with vertical antennas dispersed 4-5 kilometres from one another, with a frequency range of 10-15 kilocycles per second which will detect signals as low as 2 millivolts per metre;

(2) A device for recording the form of the signal, the device to provide recording of the form of the radio-pulse in a frequency range 500 c.p.s. - 200 kilocycles per second when the intensity of the field is 10 millivolts per metre and more;

(3) An automatic selecting device based on separating out the characteristic electromagnetic signals accompanying nuclear explosions by their form, by their spectral density and by their amplitude and a device for analysing the signal spectrum that provides display of the spectral density of the signal in the frequency range 6 - 100 kilocycles per second. Although existing techniques exclude the preponderant majority of signals from lightning, further advantage will be taken of information from the acoustic, seismic or other basic methods of detection to aid in further discrimination between signals from nuclear explosions and from lightning flashes;

(4) The requisite measuring and auxiliary apparatus and also power-supply units and means for obtaining correct radio time signals.

The site on which the antennas and the electromagnetic recording apparatus are disposed should be on flat or rolling terrain with about 300 metres clear space around the antennas, and distant from sources of electrical interference, power lines and communications lines.

D. Apparatus for collecting and analysing radioactive debris

The apparatus for collecting and analysing radioactive debris should include:

(1) A large filtering installation with a through-put capacity of 2×10^4 cubic metres of air over 10 - 24 hours, and which is used on a 24-hour basis;

(2) Equipment for collecting radioactive depositions -- a surface with about 100 square metres area should be used. During dry weather, the surface can be washed down to collect dry fallout;

(3) A laboratory for simple radiochemical analysis.

Apparatus should be located in open areas, preferably on high ground, with high precipitation frequency. Apparatus should not be located in cut-off valleys or near regions with high natural background.

E. Apparatus installed on aircraft for collecting radioactive debris and detection of a radioactive cloud.

(1) A filtering installation for aircraft should provide for the collection of the maximum quantity of the products of radioactive decay, the rate of filtering being about 3500 cubic metres an hour.

(2) The aircraft utilized for the collection of radioactive debris should have equipment for the comparatively fast determination of the presence of fresh radioactive debris.

(3) A small radiochemical laboratory will be located at each base for routine aircraft sampling flights.

Aircraft flights over ocean areas should be laid out as nearly as possible in approximately a north-south direction, and located near the sides of the major continents, as well as in the centre of oceans remote from continents.

5. All the apparatus of the control posts should be designed for reliable continuous operation.

6. Improved apparatus and techniques should be actively developed and expeditiously incorporated into the control system for the purpose of continuously improving the effectiveness for the detection and identification of nuclear explosions.

IV. CONCLUSIONS ON A CONTROL SYSTEM FOR DETECTING VIOLATIONS OF A POSSIBLE AGREEMENT ON THE SUSPENSION OF NUCLEAR TESTS

The Conference of Experts, having considered a control system for detecting violations of a possible agreement on the suspension of nuclear tests, has come to the conclusion that the methods for detecting nuclear explosions available at the present time, viz. the method of collecting samples of radioactive debris, the methods of recording seismic, acoustic, and hydroacoustic waves, and the radio-signal method, along with the use of on-site inspection of unidentified events which could be suspected of being nuclear explosions, make it possible to detect and identify nuclear explosions, including low yield explosions (1-5 kt). The Conference has therefore come to the conclusion that it is technically feasible to establish with the capabilities and limitations indicated below, a workable and effective control system to detect violations of an agreement on the worldwide suspension of nuclear weapons tests.

The Conference of Experts has come to the following conclusions regarding such a system:

1. The control system should be under the direction of an international control organ which would ensure the coordination of the activities of the control system in such a way that the system would satisfy the following technical requirements and perform the functions involved:

(a) The development, testing, and acceptance of the measuring apparatus and of the equipment, and stating the criteria for the siting of the control posts;

(b) Carrying out at the control posts and on aircraft, mentioned in items 3 and 5 of the present Conclusions, of continuous and effective observations for the phenomena which make it possible to detect nuclear explosions by the use of the methods recommended by the Conference;

(c) Reliable communication, with the aid of existing channels where they are suitable for this purpose, between the international control organ on the one hand and, on the other hand, the control posts and the bases from which the regular aircraft flights are carried out; communications and transportation should ensure the speedy transmission of the results of observations, of data (including samples), of reports, and of necessary supplies;

(d) Means of transport of personnel of the control posts in accordance with their duties and, so far as necessary, for the staff of the international control organ;

(e) Timely analysis and processing of the data from the observations of the control posts with the aim of speedily identifying events which could be suspected of being nuclear explosions, and in order to be able to report thereon in such manner as is considered by governments to be appropriate;

(f) Timely inspection of unidentified events which could be suspected of being nuclear explosions, in accordance with item 6 of the present Conclusions;

(g) Staffing of the control system (the network of control posts on land, on ships, and on aircraft, and also the staff of the international control organ) with qualified personnel having appropriate fields of specialization;

(h) Providing assistance in putting into effect a scientific research program, with the aim of raising the scientific standard of the system.

2. A network of control posts is characterized by three main parameters:

(a) The minimum yield adopted for the nuclear explosion or the natural events giving equivalent signals;

(b) The number of control posts;

(c) The probability of correct identification of natural events, particularly earthquakes.

The dependence between these parameters is such that with an increase in the yield of the explosion or the number of control posts the probability of detection and identification increases, and the number of unidentified events suspected of being a nuclear explosion decreases. On the other hand, for the identification of the increased number of unidentified events resulting from a smaller number of control posts it would be necessary to increase the number of on-site inspections or to make greater use of information coming from sources not subordinate to the international control organor, if necessary, both.

The Conference considers that the problem of detecting and identifying underground explosions is one of the most difficult, and that, to a large extent, it determines the characteristics of the network of control posts.

3. The network of control posts would include from 160 to 170 land-based control posts (equipped in accordance with Section III of this report) and about 10 ships. Of these 160-170 control posts about 100-110 would be situated in

continents, 20 on large oceanic islands, and 40 on small oceanic islands; however, the exact number of control posts within the limits indicated above, can be determined only in the process of actually disposing them around the globe, taking into account the presence of noise at the sites at which they are located, and other circumstances.

The spacing between the control posts in continental aseismic areas would be about 1700 kilometres, and in seismic areas about 1000 kilometres. The spacing between the control posts in ocean areas would vary between 2000 and more than 3500 kilometres; the spacing between island control posts in seismic areas would be about 1000 kilometres. This would lead to the following approximate distribution of control posts over the globe (with a network including 110 continental posts):
North America - 24, Europe - 6, Asia - 37, Australia - 7, South America - 16, Africa - 16, Antarctica - 4; together with 60 control posts on islands and about 10 ships.

4. The tasks of the personnel of the control posts would include the ensuring of the normal functioning of apparatus, the preliminary processing of data received, and the forwarding of these data to the international control organ and to the government of the country on whose territory the control post is located in such a manner as may be considered appropriate by governments.

In order to carry out the tasks required one might need for each control post about 30 persons with various qualifications and fields of specialization, and also some persons for the auxiliary servicing staff.

5. In addition to the basic network described, air sampling would be accomplished by aircraft carrying out regular flights along north-south routes over the oceans along the peripheries of the Atlantic and Pacific Oceans, and also over areas of the oceans which are remote from surface control posts.

When it is necessary to investigate whether a radioactive cloud is present, in the case of detection of an unidentified event which could be suspected of being a nuclear explosion, special aircraft flights would be organized in order to collect samples of radioactive debris in accordance with Section II E 10.

6. When the control posts detect an event which cannot be identified by the international control organ and which could be suspected of being a nuclear explosion, the international control organ can send an inspection group to the

site of this event in order to determine whether a nuclear explosion had taken place or not. The group would be provided with equipment and apparatus appropriate to its task in each case. The inspection group would forward a report on the investigation it had carried out to the international control organ, and to the government of the country on the territory of which the investigation was made in such a manner as may be considered appropriate by governments.

7. The network of control posts disposed as described, together with the use of aircraft as described, would have the following effectiveness, subject to the qualifications discussed in items 8 and 9:

(a) Good probability of detecting and identifying nuclear explosions of yields down to about 1 kiloton, taking place on the surface of the earth and up to 10 kilometres altitude, and good probability of detecting, but not always of identifying, explosions taking place at altitudes from 10 to 50 kilometres. In these cases the independent methods enumerated in Sections II A, II B and II D would be used.

(b) Good probability of detecting nuclear explosions of 1 kiloton yield set off deep in the open ocean. In this case use would be made of the independent hydroacoustic and seismic methods described in Sections II A and II C.

The identification of underwater explosions can, in comparatively rare cases, be made more difficult by natural events which give similar hydroacoustic and seismic signals.

(c) Good probability of recording seismic signals from deep underground nuclear explosions in continents equivalent to 1 kiloton and above. In this case use would be made of the seismic method described in Section II C.

The problem of identifying deep underground explosions is considered in item 8.

8. Along with the observation of signals of possible underground explosions the control posts would record at the same time a considerable number of similar signals from natural earthquakes. Although, with the present state of knowledge and techniques, the network of control posts would be unable to distinguish the signals from underground explosions from those of some earthquakes, it could identify as being of natural origin about 90 per cent of the continental earthquakes, whose signals are equivalent to 5 kiloton, and a

small percentage of continental earthquakes equivalent to 1 kiloton*.

It has been estimated on the basis of existing data that the number of earthquakes which would be undistinguishable on the basis of their seismic signals from deep underground nuclear explosions of about 5 kiloton yield could be in continental areas from 20 to 100 a year. Those unidentified events which could be suspected of being nuclear explosions would be inspected as described in item 6.

The capability of the control system to identify underground nuclear explosions of 1-5 kiloton yield depends on:

(a) The small fraction of earthquakes that can be identified on the basis of data obtained from the control posts alone;

(b) The fraction of earthquakes that can be identified with the aid of supplementary data obtained from existing seismic stations; and

(c) The fraction of events still left unidentified which could be suspected of being nuclear explosions and for which the international control organ carries out inspection in accordance with item 6.

Although the control system would have great difficulty in obtaining positive identification of a carefully concealed deep underground nuclear explosion, there would always be a possibility of detection of such a violation by inspection.

The on-site inspection carried out by the international control organ in accordance with item 6 would be able to identify with good probability underwater nuclear explosions with a yield of 1 kiloton and above.

9. The Conference notes that in certain special cases the capability of detecting nuclear explosions would be reduced; for instance, when explosions are set off in those areas of the ocean where the number of control posts is small

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* The Conference notes that in order to increase the percentage of earthquakes of less than 5 kiloton yield which could be identified, it would be appropriate to supplement the data from the control posts by trustworthy data from the best existing seismic stations. The results of the observations of these seismic stations should, for this purpose, be made available to the international control organ, and the equipment of the seismic stations suitable for this purpose could be improved by using the best modern apparatus.

and the meteorological conditions are unfavorable; in the case of shallow underground explosions; when explosions are set off on islands in seismic regions; and in some other cases when the explosion is carefully concealed. In some cases it would be impossible to determine exactly the area in which a nuclear explosion that had been detected took place.

However, the Conference considers that whatever the precautionary measures adopted by a violator he could not be guaranteed against exposure, particularly if account is taken of the carrying out of inspection at the site of the suspected explosion.

10. The system described does not include specific means to detect and identify nuclear explosions at high altitudes (above 30-50 kilometres). The Conference has formulated its findings on the methods of detecting nuclear explosions set off at altitudes greater than 30-50 kilometres and has characterized these methods in Section II E.

11. The Conference of Experts recommends the control system described above for consideration by governments.

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The following experts participated as delegates at the Conference:

Western Experts

Dr. James B. Fisk
Dr. Robert F. Bacher
Sir John Cockcroft
Dr. Ernest O. Lawrence
Sir William Penney
Prof. Yves André Rocard
Dr. O.M. Solandt

Delegations of:

Union of Soviet Socialist Republics

E.K. Fedorov
N.N. Semenov
I.E. Tamm
M.A. Sadovski
O.I. Leipunski
I.P. Pasechnik
K.E. Gubkin
S.K. Tsarapkin

Polish People's Republic

H. Miesowicz
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ANNEX I

CONCLUSIONS AS TO THE APPLICABILITY OF THE METHOD OF RECORDING ACOUSTIC WAVES FOR THE DETECTION OF NUCLEAR EXPLOSIONS

The Conference of Experts examined the process of propagation of the acoustic waves caused by nuclear explosions and the methods of recording these waves with the aim of determining the possibility of using them for detecting nuclear explosions.

The Conference came to the following conclusions:

1. When there are explosions in air, a strong air acoustic wave is formed which propagates over large distances. An indication of the amplitude of the air pressure wave is given by a formula which is approximately valid for a homogeneous atmosphere and according to which this amplitude is proportional to the cube root of the yield and inversely proportional to the distance. However, the amplitude of this acoustic wave is strongly dependent upon meteorological conditions and cannot be predicted accurately by a simple formula of such a kind. The observed amplitude in certain cases can be five times larger or smaller than that predicted by a formulation which includes only the energy release and the distance to detecting station.

2. Existing apparatus of special design can detect the air wave from a one kiloton explosion in the air above local background noise at relatively large distances.

The detection capability of a single station is strongly dependent upon the orientation of the propagation path to the station with respect to the upper winds. When the upper winds are mainly in one direction, a one kiloton explosion can be detected with a high degree of confidence downwind at a distance of 2,000 to 3,000 kilometres and upwind at a distance of 500 kilometres. When the upper winds are erratic and the average wind is small, such as frequently happens in the spring and fall, detection of a one kiloton explosion can be accomplished with a similar degree of confidence to a distance of approximately 1,300 kilometres independently

of the direction. On the basis of the records from three stations, the location of the explosion can be determined with an accuracy of better than 100 kilometres.

3. The acoustic apparatus at control posts at the above distances from an explosion can detect explosions which occur between the surface and a height of 30 kilometres. A reasonable extrapolation of existing experience indicates that for explosions taking place up to an altitude of about 50 kilometres there should not be a great change in the detectability of the acoustic wave. Whether a substantial acoustic wave will be generated at higher altitudes is not well known from direct experiment or from any theoretical considerations so far discussed. Deep underground and underwater explosions do not produce air waves sufficiently intense for detection purposes.

An underwater explosion in the oceans generates very strong underwater sound waves (hydroacoustic), which even in the case of small explosions can be detected at distances of about 10,000 kilometres.

4. Acoustic waves which resemble in certain cases the acoustic signals of nuclear explosions may be produced by natural events (primarily meteoric, volcanic or submarine disturbances). In such cases the identification of the event as natural or as a nuclear explosion must be based on a comparison of acoustic data with those obtained by aid of other methods.

5. The Conference of Experts recommends the inclusion of methods for the recording of acoustic, air and hydro-acoustic waves in the list of the basic methods for the detection of nuclear explosions with the aid of a network of control posts. The Conference notes that methods of recording of pressure waves may be further improved to increase the precision and the sensitivity, and to eliminate background noise and spurious signals.

ANNEX II

CONCLUSIONS AS TO THE APPLICABILITY OF THE METHOD OF USING RADIOACTIVE DEBRIS FOR DETECTING AND SUBSEQUENTLY IDENTIFYING NUCLEAR EXPLOSIONS

The Conference of Experts has studied the process of the dissemination of radioactive débris resulting from a nuclear explosion and has considered the collection of samples of radioactive débris and its analysis as one of the methods for detecting and subsequently identifying nuclear explosions. The Conference has come to the following conclusions:

1. When an explosion occurs a considerable quantity of radioactive débris is produced. If the explosion is based on a fission reaction then this quantity amounts to 3×10^8 curies per 1 kT T.N.T. equivalent of the energy of the explosion as of one hour after the reaction. Thermonuclear reactions will lead to the formation of Carbon 14, Tritium, and other radioactive substances which result from neutron irradiation and which, in principle, can also be used to detect an explosion.

2. When nuclear explosions occur between the earth's surface and a height of approximately ten kilometres the radioactive débris is thrown into the atmosphere where it is carried by winds to great distances. The concentration of this radioactive débris is greatly influenced by the vertical and horizontal distribution of the wind in the troposphere and in the lower layers of the stratosphere. The concentration is also decreased as a consequence of washing out by rain and gravitational deposition.

3. The distribution by height of the radioactive débris carried in the atmosphere will depend in the first place on the energy of the explosion, on the conditions in which the explosion took place (i.e. on the earth, under the earth, or in the air) and on the meteorological conditions at the moment of explosion. In the case of low energy explosions in the air up to a height of approximately

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* ENF/NUC/18/Rev.1 is in Russian only.

ten kilometres the radioactive débris will initially concentrate in a small volume below the tropopause. This débris will gradually get disseminated both horizontally and vertically in the troposphere and in the course of a period of from one to thirty days (depending on the turbulence of the atmosphere, the wind structure, and the dimensions of the particles which carry the radioactive substances) it can be detected close to the earth's surface, as also at various heights up to the tropopause.

4. The spreading of the cloud in the atmosphere is determined by many meteorological processes. As a result of the action of these processes the cloud is bound to reach a stage when it is mixed in a vertical direction and spread in a horizontal direction in such a way as to afford the most convenient conditions for taking samples.

Calculations and experimental data give ground for considering that this stage will be reached in the period between the fifth and twentieth day of the existence of the cloud. Before that period the cloud may be too small, both in its horizontal and its vertical extent. After thirty days have expired a considerable part of the radioactive débris will decay and a sample will constitute a lesser proportion of the natural or other background, thereby making more difficult the detection and identification of an explosion.

5. Existing radiochemical techniques make it possible to detect and identify fresh decay products in a sample of radioactive débris containing about 10^8 fissions. The time of origin of this fresh débris can be determined within five to ten per cent of its age if the sample contains about 10^{10} fissions and is not contaminated to any considerable extent by old fission products.

6. The taking of samples on the surface of the earth by a network of control posts makes it possible to carry out continual monitoring of the contamination of the air at many separate points by means of air filtration and also by collecting radioactive fallout and fallout in rain. If control posts are disposed at distances of the order of 2,000 - 3,000 kilometres then an explosion with an energy of 1 kT set off in the troposphere (0 - 10 kilometres above the surface of the earth) will be detected with a high degree of reliability in the period of five to twenty days although the place of explosion cannot be exactly determined and although the time of explosion will be determined with

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some error. Calculation shows that with favourable meteorological conditions an explosion of even lesser energy can be detected in this way.

In the course of the period of time of from two to five days after an explosion of energy equivalent to 1 kT the collection of a sample of radioactive débris from the explosion which is suitable for analysis can be effected in the air by an aircraft if the area of the supposed location of the cloud is known approximately. The taking of such a sample will make it possible to establish approximately the point of the explosion by means of using meteorological data for back-tracking the trajectory of movement of the cloud.

7. Underground or underwater explosions set off at shallow depths and accompanied by the throwing up of earth or water can also be identified by the method of collecting radioactive samples although with lesser reliability than for explosions of the same energy in the troposphere.

8. The Conference of Experts considers that systematic measurements of radioactive substances in the air and also the collection of radioactive aerosols deposited on the ground and measurements of the radioactivity of precipitation can be successfully used for the detection of nuclear explosions and also, in many cases, for assessing certain parameters relating to them even in the absence of other indications, and it recommends the inclusion of the method of collecting samples of radioactive débris in the number of basic methods for detecting and identification of nuclear explosions by a network of control posts.

The Conference of Experts recommends the utilization for a regular control service, as a method for detecting nuclear explosions, of the taking of samples of the air by aircraft over oceans. For this purpose use should be made of existing aircraft flights over the oceans which are carried out by various countries for the purposes of meteorological observations.

9. The Conference of Experts considers that the method of taking samples of radioactive débris can also be used successfully for subsequent investigation of the fact of a nuclear explosion in those cases when there are appropriate indications from other methods.

For this purpose it is possible to use the detection of radioactive débris remaining at the point of the supposed explosion (on the earth's surface, under the earth, in the water) and also the determination of the presence of a radioactive

cloud in the period between two and five days after a supposed explosion in the atmosphere in the area where the cloud is calculated to be by the time of investigation.

In such a case search for the radioactive cloud can be made on an aircraft having equipment for the taking of a sample of radioactive débris. To this end use should be made chiefly of the aircraft flights over the oceans made for the purposes of meteorological observations.

10. In some cases use can be made of aircraft flights over the territories of the USA, the USSR, the UK and other countries to collect air samples for the purpose of checking on data obtained by other methods of detection of nuclear explosions.

The Experts consider that to accomplish this task it would be quite sufficient to make use of the aircraft of the country being overflown and that in such cases it is sufficient that flights for the purpose specified should be made along routes laid down in advance. Representatives of the USSR, the USA, the UK or other States participating in the operation of the control system may be on board these aircraft in the capacity of observers.

11. The Experts note that in the course of time the sensitivity and efficiency of the method of collecting radioactive débris will increase, as a consequence of the atmosphere becoming cleared of the radioactive products it contains, as also as a result of the perfection of the techniques for collecting and analysing samples.

ANNEX III

CONCLUSIONS AS TO THE APPLICABILITY OF THE METHOD OF RECORDING SEISMIC WAVES FOR THE DETECTION OF NUCLEAR EXPLOSIONS

The Conference has considered the processes of propagation of seismic waves generated by nuclear explosions and the methods for recording these waves for the purpose of determining the possibility of using them for the detection of underground and underwater nuclear explosions. The Conference has come to the following conclusions:

1. When nuclear explosions occur under the ground or under the water, longitudinal, transverse and surface waves are formed and get propagated to great distances. The first longitudinal wave is the most important, both for detecting an explosion and for determining the place of the explosion, and also for distinguishing an earthquake from explosions. Transverse and surface waves also help to define the nature of a seismic perturbation.

2. Longitudinal seismic waves caused by underground nuclear explosions set off under conditions analogous to those in which the Rainier** shot occurred can be detected and the direction of first motion of the longitudinal wave can be determined at a distance of approximately 1,000 kilometres, and also at distances of approximately 2,000-3,000 kilometres at sites which are considerably more quiet than the average for:

(a) Explosions of the order of one kiloton recorded during periods of favourable noise conditions

(b) Explosions of the order of five kilotons recorded during periods of unfavourable noise conditions.

It must be noted that all seismic stations situated at thousands of kilometres from one another cannot have an identically high or identically low level of background at one and the same time.

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* ENP/NUC/19/Rev.1 is in Russian only.

** The underground nuclear explosion "Rainier" with an energy of 1.7 kilotons (Nevada) was set off in unfavourable conditions for transferring energy to the ground. However, even worse conditions of coupling are possible.

3. Conditions for detection and identification of underwater explosions set off in shallow water but at a sufficient depth, are considerably more favourable than conditions for detecting underground explosions.

4. Control posts carrying out seismic observations should be put at sites with a minimal level of microseismic background, such as are possible in internal continental regions. Such stations, when provided with arrays of seismographs, can ensure the obtaining of the data indicated above. However, at stations which are in unfavourable regions such as coastal and island regions the noise level will be higher than at quiet stations inside continents. In those cases for detection and determination of the sign of first motion the energy of the explosion must increase in the ratio of the power of 3/2 with respect to the increase of background level. This is in part compensated by the fact that quiet stations inside continents will record more powerful explosions at distances of from 2,000 to 3,500 kilometres. Bursts with an energy of 5 kilotons and more will be detected by quiet stations placed at the distances named.

5. The majority of earthquakes can be distinguished from explosions with a high degree of reliability if the direction of first motion of the longitudinal wave is clearly recorded at 5 or more seismic stations on various bearings from the epicentre. Thus not less than 90 per cent of all earthquakes taking place in continents can be identified. The remaining 10 per cent or less of cases will require the analysis of additional seismograms where this is possible; and for this purpose use must also be made of the data of the existing network of seismic stations. If required, these supplementary stations should be further equipped with improved apparatus. In relatively aseismic areas it is sufficient merely to define the position of the epicentre. In this connexion cases of detection of seismic events will be regarded as suspicious and will require further investigation with the help of other methods. For those cases which remain unidentified inspection of the region will be necessary.

In regions where the regular disposition of seismic stations in quiet conditions is not possible, the percentage of correct identification of earthquakes will be less.

With modern methods and making use of the data of several surrounding seismic stations the area within which an epicentre is localized can be assessed as approximately 100-200 square kilometres.

6. The Conference of Experts recommends the inclusion of the method of recording seismic waves in the number of basic methods for detecting nuclear explosions with the help of a network of control posts. The Conference notes that the range and accuracy of recording and identifying underground nuclear explosions can be improved in the future by means of perfecting the methods of recording seismic waves, both by way of perfecting apparatus and also by way of perfecting the methods for differentiating an earthquake from explosions.

ANNEX IV

CONCLUSIONS AS TO THE APPLICABILITY OF RECORDING OF RADIO SIGNALS FOR THE DETECTION OF NUCLEAR EXPLOSIONS

The Conference of Experts considered the generation and propagation of radio pulses originating from a nuclear explosion and the methods of recording these signals in order to determine the possibility of using them for the detection of nuclear explosions. The Conference came to the following conclusions:

1. In the case of a nuclear explosion in the atmosphere, there arises a powerful electromagentic radiation (radio signal), caused by the gamma radiation accompanying the explosion. In the case of underground, underwater, or specially shielded explosions radio emissions are not expected which can be recorded at great distances by modern techniques.

When the explosion is carried out on or above the surface of the earth (water) and without specially constructed layers to absorb gamma rays, the energy and spectral distribution of the radio signal are such that its essential components are propagated over the whole terrestrial globe. The strength of the radio signal depends upon certain features of the construction of the bomb and on the altitude of the explosion. An explosion of 1 kiloton yield can be detected by means of radio signals at distances exceeding 6,000 km assuming that in the neighbourhood of the receiving station there is no high noise level from local thunderstorms or other sources.

By radio direction finding methods, it is possible to determine the azimuth of the signal source with an accuracy of about 2°, i.e., about 30 km at a distance of 1,000 km. The time of production of the signal may be established with an accuracy of several milliseconds. The attainment of such accuracy depends on the choice of sufficiently flat location and on the absence of electrical interference at the receiving site.

2. Lightning flashes emit radio signals in the same frequency range and act as interference for the method of detection of a nuclear explosion by means of its radio signal.

Close to the source of radiation, the forms of radio signals from lightning and from nuclear explosions examined to date are quite different. However, at distances exceeding 1,000 kilometres, due to the distortion of the form of radio signals in the wave guide formed by the earth and the ionosphere, the form of radio signals from some individual lightning flashes is similar to the signal from nuclear explosions. The number of signals from lightning flashes recorded by apparatus without using special techniques of signal selection depends on the sensitivity of the apparatus and on the locality, and can amount to from ten to several hundred signals per second. Existing techniques can be applied to exclude automatically the preponderant majority of signals from lightning. The distinction of the remaining signals due to atmospherics from those due to nuclear explosions requires the application of special methods of discrimination, including criteria on form of signal, spectral distribution and distance to source of radiation.

In the present state of the technique of the discrimination of signals in some individual cases the record of a signal cannot be identified either as coming from a nuclear explosion or from lightning.

3. The Conference of Experts recommends that further research should be carried out in order to understand more fully the physical properties of atmospherics involved in differentiating signals from nuclear explosions and atmospherics, by means of the development of the theory of this problem, the collection and systematization of data about atmospherics and the development of suitable automatic instruments. The Conference considers that there are good prospects for improvement of procedures of signal discrimination.

4. Theoretical considerations suggest that recording of radio signals can be used to detect nuclear explosions occurring at altitudes up to the order of 1,000 kilometres.

5. The Conference of Experts recommends the inclusion of recording of radio signals among the methods of detecting nuclear explosions.

ANNEX V

CONCLUSIONS AS TO THE METHODS OF DETECTION OF NUCLEAR EXPLOSIONS CARRIED OUT AT HIGH ALTITUDE (MORE THAN 30 TO 50 KM) ABOVE THE EARTH

The Conference of Experts has given theoretical consideration to the gamma radiation and neutrons resulting from a nuclear explosion and the conditions of recording them from earth satellites; and to optical phenomena and ionization of the air in the upper layers of the atmosphere in the case of a high altitude explosion (altitudes above 30 - 50 km) and has arrived at the following conclusions:

1. A kiloton nuclear explosion produces at its source delayed gamma-rays from fission products, and prompt gamma-rays and neutrons. The number of prompt gamma-rays and neutrons depends upon the construction of the device and upon the materials surrounding it. The delayed gamma-rays are insignificantly affected by these factors. At a distance of 10^4 kilometres in vacuo, typical quantities of radiation from a one kiloton fission explosion are:

(a) Delayed gamma-rays

10^4 quanta/cm^2 during the first second

(b) Prompt gamma-rays*

10^2 quanta/cm^2

distributed over a time of about 10^{-7} sec.

(c) Neutrons

10^4 neutrons/cm^2

distributed over a time of a few seconds.

The cosmic background at the height at which earth satellites orbit is under study at the present time, attention being paid to the quantity, nature and energy of the particles; however, on the basis of preliminary data, it can be considered that the detection of an explosion from an earth satellite is possible, by means of recording the gamma-rays accompanying the nuclear

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* Special shielding of the exploding device can considerably reduce the gamma-radiation accompanying the reaction, but cannot reduce the radiation from fission products. However, such shielding involves increasing by several times the weight of the whole device.

reaction, neglecting shielding, and also by means of recording the gamma rays of the fission products and the neutrons. If both prompt gamma rays and neutrons are recorded, it is possible to get a rough idea of the distance to the explosion. The use of gamma-rays from a nuclear explosion will make it possible to detect the explosion in cosmic space at a distance of the order of hundreds of thousands of kilometres from the earth. Estimate of the maximum distance for the detection requires data concerning the magnitude of the cosmic radiation at the orbit of the earth satellite. If there is an explosion at a height of 30 - 50 km and above, and if the height at which the earth satellite orbits is some thousands of kilometres, one can neglect the absorption of gamma quanta in the upper layers of the atmosphere. The Conference of Experts considers that it is possible to use for the detection of nuclear explosions at high altitudes the recording of gamma radiation and neutrons with properly instrumented earth satellites.

2. In the case of an explosion at a great height light will be emitted at the point of the explosion and there will be luminescence in the upper layers of the atmosphere under the action of X-rays and fast atoms from the materials in the device. Light phenomena may be detectable from the surface of the earth in clear weather at night with the help of simple apparatus; in day time with the help of more sensitive apparatus. In cloudy weather the detection of optical phenomena from stations on the earth's surface would probably be extremely difficult.

The radiation from a nuclear explosion creates in the upper layers of the atmosphere a region of increased ionization which is detectable by the absorption of cosmic radio-signals or by anomalies in the propagation of radio waves.

Our knowledge of the absorption of cosmic noise by ionospheric phenomena is not sufficient to determine the number of natural events similar to those resulting from a nuclear explosion.

The Conference of Experts considers that it is possible to use the recording of ionospheric phenomena, using appropriate radio techniques, and of optical phenomena for the detection of nuclear explosions at high altitudes.

3. The Conference of Experts has not considered the problem of the detection of nuclear explosions which might be conducted in cosmic space at distances of millions of kilometres from the earth.

ANNEX VI

CONCLUSIONS AS TO THE QUESTION OF THE TECHNICAL EQUIPMENT OF THE CONTROL SYSTEM FOR THE DETECTION AND IDENTIFICATION OF NUCLEAR EXPLOSIONS

The Conference of Experts has considered the questions related to the technical equipment of a control net intended to detect and identify nuclear explosions.

The Conference has come to the following conclusions:

1. The posts of the control net situated in continents should regularly be equipped with apparatus for the detection of explosions by the acoustic and seismic methods and also by the methods of recording radio signals and of collecting radioactive debris.

2. Certain posts situated on islands or near the shores of oceans should be equipped, in addition to the methods just mentioned, with apparatus for hydroacoustic detection of explosions.

3. Posts located on ships stationed or drifting within specified ocean areas should be equipped with apparatus for the detection of explosions by the method of collecting radioactive debris and by the hydroacoustic method. The method of recording radio signals and the acoustic method might also be used on ships if suitable equipment is developed, but the effectiveness of these two methods, particularly the acoustic one, will be considerably less than on land.

4. The apparatus installed at posts of the control network must be uniform and must satisfy the following basic technical requirements:

A. Seismic apparatus

The seismic apparatus of the control post should include:

(1) Approximately 10 short-period vertical seismographs dispersed over a distance of 1.5 - 3 kilometres and connected to the recording system by lines of cable. The seismographs should have a maximum magnification of the order of 10^6 at a frequency of 1 c.p.s. and a receiving band adequate to reproduce the characteristic form of the seismic signal;

(2) 2 horizontal seismographs with the parameters indicated in point (1);

(3) One three-component installation of long-period seismographs having a broad receiving band and a constant magnification of the order of 10^3 - 2 x 10^3 in the period range 1 - 10 seconds;

(4) One three-component installation of seismographs with a narrow receiving band and magnification of the order of 3×10^4 when T = 2 - 2.5 seconds;

(5) At certain posts one three-component installation of long-period seismographs with magnification of the order of 10^4 - 2×10^4 at periods of T = 25 seconds;

(6) Auxiliary equipment necessary in order to get precise records of the seismic signal; recording devices, chronometers, power supply units and apparatus for receiving automatic radio-signals giving correct time.

The seismic apparatus should be installed in places with a minimal level of micro-seismic background, away from industrial areas, and on outcrops of bedrock (where possible). The seismographs should be installed in suitable vaults.

The area required for installing the seismic apparatus should be about 3 x 3 kilometres.

B. Acoustic apparatus

(1) The infra-acoustic equipment for a control post should include not less than three sets of microbarographic units each of which should have: a system for averaging out turbulent noise, a pressure sensing unit, a transmission line and appropriate electronic amplifiers and automatic writing instruments;

(2) The sensitivity of the microbarographic stations must ensure recording of acoustic signals in the period range 0.5 - 40 seconds, with an amplitude of 0.1 dynes per cm^2;

(3) The pressure sensing units of the microbarographs should be dispersed at about 10 kilometres from one another in order to determine the direction of arrival of the acoustic signal and the speed of propagation of the signal;

(4) The hydroacoustic apparatus for a post, which is recommended for use only in oceanic zones, should include several hydrophones placed in the main submarine sound channel.

The hydrophones should be connected with the recording station on the coast by cables. Recordings of the hydroacoustic signal should be made in several frequency sub-ranges, covering a general frequency range of from one cycle per second to several thousand cycles per second.

The infra-acoustic equipment operates best in areas of low surface winds and flat terrain covered with trees or shrubs.

C. Apparatus for recording a radio signal

The apparatus for recording a radio signal should consist of:

(1) A loop-shaped radio direction finder or a radio direction finder with vertical antennas dispersed 4 - 5 kilometres from one another, with a frequency range of 10 - 15 kilocycles per second which will detect signals as low as 2 millivolts per metre;

(2) A device for recording the form of the signal, the device to provide recording of the form of the radio-pulse in a frequency range 500 c.p.s. - 200 kilocycles per second when the intensity of the field is 10 millivolts per metre and more;

(3) An automatic selecting device based on separating out the characteristic electromagnetic signals accompanying nuclear explosions by their form, by their spectral density and by their amplitude, and a device for analysing the signal spectrum that provides display of the spectral density of the signal in the frequency range 6 - 100 kilocycles per second. Although existing techniques exclude the preponderant majority of signals from lightning, further advantage will be taken of information from the acoustic, seismic or other basic methods of detection to aid in further discrimination between signals from nuclear explosions and from lightning flashes;

(4) The requisite measuring and auxiliary apparatus and also power-supply units and means for obtaining correct radio time signals.

The site on which the antennas and the electromagnetic recording apparatus are disposed should be on flat or rolling terrain with about 300 metres clear space around the antennas, and distant from sources of electrical interferences, power lines and communications lines.

D. Apparatus for collecting and analysing radioactive débris

The apparatus for collecting and analysing radioactive débris should include:

(1) A large filtering installation with a through-put capacity of 2×10^4 cubic metres of air over 10 - 24 hours, and which is used on a 24-hour basis;

(2) Equipment for collecting radioactive depositions -- a surface with about 100 M^2 area should be used. During dry weather, the surface can be washed down to collect dry fallout;

(3) A laboratory for simple radiochemical analysis.

Apparatus should be located in open ground, preferably on high ground, with high precipitation frequency. Apparatus should not be located in cut-off valleys or near regions with high natural background.

B. Apparatus installed on aircraft for collecting radioactive débris and detection of a radioactive cloud

(1) A filtering installation for aircraft should provide for the collection of the maximum quantity of the products of radioactive decay, the rate of filtering being about 3500 cubic metres an hour.

(2) The aircraft utilized for the collection of radioactive debris should have equipment for the comparatively fast determination of the presence of fresh radioactive debris.

(3) A small radiochemical laboratory will be located at each base for routine aircraft sampling flights.

Aircraft flights over ocean areas should be laid out as nearly as possible in approximately a north-south direction, and located near the sides of the major continents, as well as in the centre of oceans remote from continents.

5. All the apparatus of the control posts should be designed for reliable continuous operation.

6. Improved apparatus and techniques should be actively developed and expeditiously incorporated into the control system for the purpose of continuously improving the effectiveness for the detection and identification of nuclear explosions.

ANNEX VII

CONCLUSIONS ON A CONTROL SYSTEM FOR DETECTING VIOLATIONS OF A POSSIBLE AGREEMENT ON THE SUSPENSION OF NUCLEAR TESTS

The Conference of Experts, having considered a control system for detecting violations of a possible agreement on the suspension of nuclear tests, has come to the conclusion that the methods for detecting nuclear explosions available at the present time, viz. the method of collecting samples of radioactive débris, the methods of recording seismic, acoustic, and hydroacoustic waves, and the radio-signal method, along with the use of on-site inspection of unidentified events which could be suspected of being nuclear explosions, make it possible to detect and identify nuclear explosions, including low yield explosions (1-5 kiloton). The Conference has therefore come to the conclusion that it is technically feasible to establish, with the capabilities and limitations indicated below, a workable and effective control system to detect violations of an agreement on the worldwide suspension of nuclear weapons tests.

The Conference of Experts has come to the following conclusions regarding such a system:

1. The control system should be under the direction of an international control organ which would ensure the coordination of the activities of the control system in such a way that the system would satisfy the following technical requirements and perform the functions involved:

(a) The development, testing, and acceptance of the measuring apparatus and of the equipment, and stating the criteria for the siting, of the control posts;

(b) Carrying out at the control posts and on aircraft, mentioned in items 3 and 5 of the present Conclusions, of continuous and effective observations for the phenomena which make it possible to detect nuclear explosions by the use of the methods recommended by the Conference;

(c) Reliable communication, with the aid of existing channels where they are suitable for this purpose, between the international control organ on the one hand and, on the other hand, the control posts and the bases from which the regular aircraft flights are carried out; communications and transportation should ensure the speedy transmission of the results of observations, of data (including samples), of reports, and of necessary supplies;

(d) Means of transport of personnel of the control posts in accordance with their duties and, so far as necessary, for the staff of the international control organ;

(e) Timely analysis and processing of the data from the observations of the control posts with the aim of speedily identifying events which could be suspected of being nuclear explosions, and in order to be able to report thereon in such manner as is considered by governments to be appropriate;

(f) Timely inspection of unidentified events which could be suspected of being nuclear explosions, in accordance with item 6 of the present Conclusions;

(g) Staffing of the control system (the network of control posts on land, on ships, and on aircraft, and also the staff of the international control organ) with qualified personnel having appropriate fields of specialization;

(h) Providing assistance in putting into effect a scientific research programme, with the aim of raising the scientific standard of the system.

2. A network of control posts is characterized by three main parameters:

(a) The minimum yield adopted for the nuclear explosion or the natural events giving equivalent signals;

(b) The number of control posts;

(c) The probability of correct identification of natural events, particularly earthquakes.

. The dependence between these parameters is such that with an increase in the yield of the explosion or the number of control posts the probability of detection and identification increases, and the number of unidentified events suspected of being a nuclear explosion decreases. On the other hand, for the identification of the increased number of unidentified events resulting from a smaller number of control posts it would be necessary to increase the number of on-site inspections or to make greater use of information coming from sources not subordinate to the international control organ or, if necessary, both.

The Conference considers that the problem of detecting and identifying underground explosions is one of the most difficult, and that, to a large extent, it determines the characteristics of the network of control posts.

3. The network of control posts would include from 160 to 170 land-based control posts (equipped in accordance with Conclusion [illegible]/ITC/23/Rev.1) and about 10 ships. Of these 160-170 control posts about 100-110 would be situated in continents, 20 on large oceanic islands, and 40 on small oceanic islands; however the exact number of control posts, within the limits indicated above, can be determined only in the process of actually disposing them around the globe, taking into account the presence of noise at the sites at which they are located, and other circumstances.

The spacing between the control posts in continental aseismic areas would be about 1,700 kilometres, and in seismic areas about 1,000 kilometres. The spacing between the control posts in ocean areas would vary between 2,000 and more than 3,500 kilometres; the spacing between island control posts in seismic areas would be about 1,000 kilometres. This would lead to the following approximate distribution of control posts over the globe (with a network including 110 continental posts): North America - 24, Europe - 6, Asia - 37, Australia - 7, South America - 16, Africa - 16, Antarctica - 4; together with 60 control posts on islands and about 10 ships.

4. The tasks of the personnel of the control posts would include the ensuring of the normal functioning of apparatus, the preliminary processing of data received, and the forwarding of these data to the international control organ and to the government of the country on whose territory the control post is located in such a manner as may be considered appropriate by governments.

In order to carry out the tasks required one might need for each control post about 30 persons with various qualifications and fields of specialization, and also some persons for the auxiliary servicing staff.

5. In addition to the basic network described, air sampling would be accomplished by aircraft carrying out regular flights along north-south routes over the oceans along the peripheries of the Atlantic and Pacific Oceans, and also over areas of the oceans which are remote from surface control posts.

When it is necessary to investigate whether a radioactive cloud is present, in the case of detection of an unidentified event which could be suspected of being

a nuclear explosion, special aircraft flights would be organized in order to collect samples of radio-active débris in accordance with Conclusions EXP/NUC/18/Rev.2.

6. When the control posts detect an event which cannot be identified by the international control organ and which could be suspected of being a nuclear explosion, the international control organ can send an inspection group to the site of this event in order to determine whether a nuclear explosion had taken place or not. The group would be provided with equipment and apparatus appropriate to its task in each case. The inspection group would forward a report on the investigation it had carried out to the international control organ, and to the government of the country on the territory of which the investigation was made in such a manner as may be considered appropriate by governments.

7. The network of control posts disposed as described, together with the use of aircraft as described, would have the following effectiveness, subject to the qualifications discussed in items 8 and 9:

(a) Good probability of detecting and identifying nuclear explosions of yields down to about 1 kiloton, taking place on the surface of the earth and up to 10 kilometre altitude, and good probability of detecting, but not always of identifying, explosions taking place at altitudes from 10 to 50 kilometres. In these cases the independent methods enumerated in Conclusions EXP/NUC/7/Rev.1, EXP/NUC/18/Rev.2 and EXP/NUC/20/Rev.1 would be used;

(b) Good probability of detecting nuclear explosions of 1 kiloton yield set off deep in the open ocean. In this case use would be made of the independent hydroacoustic and seismic methods described in Conclusions EXP/NUC/7/Rev.1 and EXP/NUC/19/Rev.2.

The identification of underwater explosions can, in comparatively rare cases, be made more difficult by natural events which give similar hydroacoustic and seismic signals;

(c) Good probability of recording seismic signals from deep underground nuclear explosions in continents equivalent to 1 kiloton and above. In this case use would be made of the seismic method described in Conclusions EXP/NUC/19/Rev.2.

The problem of identifying deep underground explosions is considered in item 8.

8. Along with the observation of signals of possible underground explosions the control posts would record at the same time a considerable number of similar signals from natural earthquakes. Although, with the present state of knowledge

and techniques, the network of control posts would be unable to distinguish the signals from underground explosions from those of some earthquakes, it could identify as being of natural origin about 90 per cent of the continental earthquakes, whose signals are equivalent to 5 kilotons, and a small percentage of continental earthquakes equivalent to 1 kiloton.*

It has been estimated on the basis of existing data that the number of earthquakes which would be undistinguishable on the basis of their seismic signals from deep underground nuclear explosions of about 5 kiloton yield could be in continental areas from 20 to 100 a year. Those unidentified events which could be suspected of being nuclear explosions would be inspected as described in item 6.

The capability of the control system to identify underground nuclear explosions of 1-5 kiloton yield depends on:

(a) The small fraction of earthquakes that can be identified on the basis of data obtained from the control posts alone;

(b) The fraction of earthquakes that can be identified with the aid of supplementary data obtained from existing seismic stations; and

(c) The fraction of events still left unidentified which could be suspected of being nuclear explosions and for which the international control organ carries out inspection in accordance with item 6.

Although the control system would have great difficulty in obtaining positive identification of a carefully concealed deep underground nuclear explosion, there would always be a possibility of detection of such a violation by inspection.

The on-site inspection carried out by the international control organ in accordance with item 6 would be able to identify with good probability underwater nuclear explosions with a yield of 1 kiloton and above.

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* The Conference notes that in order to increase the percentage of earthquakes of less than 5 kiloton yield which could be identified, it would be appropriate to supplement the data from the control posts by trustworthy data from the best existing seismic stations. The results of the observations of these seismic stations should, for this purpose, be made available to the international control organ, and the equipment of the seismic stations suitable for this purpose could be improved by using the best modern apparatus.

9. The Conference notes that in certain special cases the capability of detecting nuclear explosions would be reduced; for instance, when explosions are set off in those areas of the ocean where the number of control posts is small and the meteorological conditions are unfavourable; in the case of shallow underground explosions; when explosions are set off on islands in seismic regions; and in some other cases when the explosion is carefully concealed. In some cases it would be impossible to determine exactly the area in which a nuclear explosion that had been detected took place.

However, the Conference considers that, whatever the precautionary measures adopted by a violator, he could not be guaranteed against exposure, particularly if account is taken of the carrying out of inspection at the site of the suspected explosion.

10. The system described does not include specific means to detect and identify nuclear explosions at high altitudes (above 30-50 kilometres). The Conference has formulated its findings on the methods of detecting nuclear explosions set off at altitudes greater than 30-50 kilometres and has characterized these methods in Conclusions ENP/NUC/21/Rev.1.

11. The Conference of Experts recommends the control system described above for consideration by governments.

APPENDIX 2

CONFERENCE ON THE DISCONTINUANCE OF NUCLEAR WEAPON TESTS

Official Records

Thursday, 11 February 1960, at 4 p.m.
Palais des Nations, Geneva.

VERBATIM RECORD OF THE ONE HUNDRED AND SEVENTEENTH PLENARY MEETING

Chairman: Sir Michael WRIGHT (United Kingdom)

LIST OF MEMBERS OF DELEGATIONS PRESENT AT THE TABLE

United Kingdom:	Sir Michael WRIGHT
	Dr. P. PANTON
	Mr. H.T. MORGAN
Union of Soviet Socialist Republics:	Mr. S.K. TSARAPKIN
	Mr. I.P. PASECHNIK
	Mr. I.G. USACHEV
	Mr. O.A. GRINEVSKY
United States of America:	Mr. J.J. WADSWORTH
	Mr. D. POPPER
	Dr. C. WALSKE
	Mr. D. MARK
	Mr. D. MORRIS
Representative of the Secretary-General:	Mr. T.G. NARAYANAN

The CHAIRMAN (United Kingdom): The one hundred and seventieth meeting of the Conference is open. Does any representative wish to speak?

Mr. WADSWORTH (United States of America): Today I should like to turn from the matters we have been considering in recent meetings and to make a statement on a subject we believe to be of critical importance for this Conference. That subject is the extent to which we can overcome the principal technical obstacle in the way of agreement among our three delegations, namely, the problem of the detection and identification of underground nuclear explosions. My delegation has a proposal to make with regard to this problem.

From the very beginning of these negotiations it has been clear that a fundamental requirement exists which must be fulfilled if a satisfactory treaty is to be concluded. Such a treaty must lay down a system of effective and adequate control so that violation and evasion could not go undetected, and such a control system must be soundly based on the best available scientific data and analysis. All three of our Governments have acknowledged the existence of this requirement. For its part the United States continues to regard the requirement as an essential element in our discussions.

The experts who met in Geneva in the summer of 1958 sought to set down on paper the technical foundation for an adequately safeguarded treaty. Their report constitutes a landmark in the field of international control. They quickly recognized that the problem of detecting and identifying underground nuclear explosions would be difficult. Working largely on the basis of experimental data derived from the only underground nuclear detonation which had then taken place, they reached conclusions which at the time appeared to them to be reasonable.

Since the report of the Conference of Experts was published, the volume of experimental data on underground nuclear detonations has increased enormously, not only as a result of the Hardtack series of explosions undertaken in October 1958, but also as a result of theoretical and operational advances in the science of seismology. The significance of the new seismic data obtained from the Hardtack tests was quickly recognized in the United States, and, as my colleagues are aware, the new information was first communicated to this Conference on 5 January 1959. My delegation has always regretted that because of the unyielding resistance of the Soviet delegation almost a year elapsed before it was possible for the scientists of our three countries to undertake a joint examination of the implications of the new data.

(Mr. Wadsworth, United States)

When the Soviet Union at last agreed that Technical Working Group 2 should be convened in November 1959, we hoped that full discussion on a purely scientific basis of all the new material would result in a common assessment of the situation with respect to the detection and identification of underground nuclear explosions. We had hoped that a concerted appraisal of the clearly revealed difficulties in this area would lead to an agreed technical basis for pursuing treaty negotiations and for resolving outstanding technical problems.

Unfortunately this was not the case. Despite our best efforts it was not possible to obtain a joint reassessment of the conclusions of the Geneva Conference of Experts. Thus, it has proved impossible to convince the Soviet scientists that the experts' conclusions required modification in certain respects before they could be used as a basis for specific treaty provisions.

I have reviewed these developments not in order to engage in polemics about the past but to highlight the fact that we have reached an impasse on the technical issues of international control as regards the underground environment. I am not here engaged in praise or in blame. I am merely stating that as we see it the technical facts presented by the United States experts have demonstrated that adequate control of underground nuclear testing is far more difficult than the Geneva experts thought in 1958. The existence of these technical facts confronts all of us with a serious challenge as diplomats seeking mutually acceptable arrangements for the discontinuance of nuclear weapon tests.

I have already made it very clear that the United States would much prefer to be able to enter at once into an agreement for the cessation of all nuclear weapon tests. But it cannot do so on faith alone. The United States is prepared to agree to the cessation of nuclear weapon test explosions in those environments where adequate control is possible under a control system acceptable to us all. However, the United States cannot agree to a prohibition of testing in areas where controls cannot be effectively maintained. My colleagues will recall that I made a very similar statement on 12 January when we resumed this particular series of meetings.

(Mr. Wadsworth, United States)

Let me emphasize that our objective has been and continues to be to seek a political solution enabling us to progress as rapidly as possible toward a treaty including an adequately monitored cessation of all nuclear weapon tests. In the light of our current difficulties such a solution must, we believe, possess four characteristics. First, while acknowledging the areas of technical disagreement between Western and Soviet scientists as regards criteria for the identification of seismic events, such a solution should seek to circumvent them. Second, it should similarly circumvent existing disagreements regarding equivalent kiloton yields of events of given seismic magnitude. Third, it should allow us to proceed immediately to consolidate and codify the widest possible area of workable agreement, in the light of the technical convictions. Fourth -- and I would stress this aspect of the matter -- such a solution should provide for the progressive extension of this area of agreement as rapidly as such extension is technically warranted.

On the instructions of my Government, therefore, I propose that we, at this Conference, move immediately to negotiate a phased agreement on the cessation of nuclear weapon tests. The first phase of the agreement -- which could be put into effect in the near future -- should, in our view, provide for the cessation of all nuclear weapon tests in the earth's atmosphere, in the oceans, and in outer space up to the greatest height with respect to which agreement can be reached on the installation of effective controls.

This phase should include provision for the cessation of underground nuclear tests down to the lowest limit of size, or threshold, for which, in our judgment, adequate control is now feasible. This threshold would be defined in terms of the magnitude of seismic events detected by the control system. I am here referring to the control network recommended by the Geneva experts in 1958. Under this approach there would be a direct relationship between, on the one hand, the number of on-site inspections of detected but unidentified seismic events of magnitudes greater than the threshold magnitude, and, on the other, the number of such events which occur. This means, of course, that, within the limits of the technical capability of the agreed control system, the selection of an agreed specific threshold will depend, in part, upon the level of inspection acceptable to the three countries represented here. To state the position in simplest terms, a high threshold would result in fewer unidentified events, and thus in a reduced need for inspection. A low threshold would have the opposite effect.

(Mr. Wadsworth, United States)

I wish to stress that we have a dynamic concept of phasing. We certainly do not regard our current capabilities in seismic technology as fixed and unchanging. On the contrary, it remains as much as ever a policy of the United States ultimately to achieve a comprehensive treaty prohibiting all nuclear tests, and to achieve it as rapidly as the technology of control allows. Not only that: my Government will be as active as it can in encouraging technological progress towards improved methods of control.

Under our approach the treaty would provide for the evolutionary and progressive lowering of the threshold magnitude as the detection and identification capabilities of the system were improved through the utilization of improved techniques, instrumentation, and criteria. In this connexion I am happy to be able to say that the United States has embarked on a major experimental programme aimed at the discovery and development of improved means of seismic detection and identification. In pursuing this programme we shall make use of all essential methods and techniques of scientific research, and shall feel free to utilize nuclear detonations should these be required.

At the same time, we recognize that even the best and most conscientious efforts of one country in research are not likely to prove as rewarding as the joint efforts of several countries. All three nations here represented have, in the past, made major contributions to knowledge in the science of seismology. These advances could undoubtedly be accelerated through the pooling of research and elimination of duplication. In this respect it is encouraging that the one subject on which the three delegations of experts did reach agreement last December in Technical Working Group 2 was that of improvements and potential improvements in the seismic control system and in the techniques which it will use.

We therefore propose, as part of our projected approach, that our three countries should institute a programme of joint research in this field as rapidly as it can be agreed. There are many possibilities for co-ordination and for the exchange of information, but we can go even further toward actual collaboration in projects and experiments. It would be understood that the results of our labours would be incorporated into the control system as soon as they had reached a technologically useful state, and this would, in turn, allow us to consider to what extent each advance might permit us to lower the threshold magnitude or

(Mr. Wadsworth, United States)

otherwise move nearer to a comprehensive treaty. This programme of joint research could be continued under the supervision of the control commission after that body had been established, since a research programme is already among the commission's functions under agreed provisions of draft article VI.

My Government believes that it would be helpful if we could agree that the criteria for identification proposed by United States experts in Technical Working Group 2 could be used by the control system in the initial phase of the treaty. This would go far to meet any concern as to the range of events to which an agreed level of inspection could be applied. The use of these criteria would enable the control organization to limit the number of events eligible for inspection to the lowest figure which we are convinced is consistent with existing technical and scientific knowledge. If we can agree to employ these criteria, my delegation would propose that the agreed level of inspection should apply only to those seismic events above the threshold magnitude which cannot be identified by their application. This procedure has the decided practical advantage that it will permit reduction of the number of inspections which may be required when and as improvements in techniques occur and better criteria for identification of seismic events are developed and agreed upon.

If, however, we are unable here to reach agreement on criteria for identification, we would alternatively propose, as a way round this difficulty, that pending such agreement the agreed level of inspection be expressed simply as a percentage of all seismic events above the agreed threshold magnitude which are located by the system. In either case, of course, each side would have the right to select from those events eligible for inspection the particular events which it wished to have inspected on the territory of the other side.

I should like to recall that my delegation has made it clear, notably at our one hundred and twenty-eighth meeting, that the question of whether the level of inspection should be expressed as some percentage figure of unidentified seismic events, or whether it should be expressed as a fixed numerical quota, is of secondary importance. The primary consideration, as we have stated many times, is that the level of on-site inspection must bear an appropriate relationship to the scientific facts, to the detection capabilities of the system, and thus to the number of seismic events which the seismic component of the control system cannot identify. Accordingly, if the other delegations prefer, my delegation

(Mr. Wadsworth, United States)

would be willing to express the level of inspection in numerical terms. Initially we would base such a number on an agreed percentage of the current United States scientific estimates of the annual number either of located events or of unidentified events above the agreed threshold magnitude. This numerical quota of inspections would be subject to revision at least annually, by applying the agreed percentage to the number of events which had actually occurred in the previous period.

As I said earlier, the specific threshold magnitude to be adopted under this approach would depend in large part on the level of inspection that the other delegations were prepared to accept. However, as a specific proposal under this approach my delegation is authorized to suggest the adoption of a threshold of magnitude 4.75 on the unified magnitude scale in common use by seismologists. Thus, depending on whether we are able to reach agreement on criteria, either all seismic events of magnitude greater than 4.75 located by the system would be eligible for inspection or, alternatively, only those events above such magnitude left unidentified after the application of the United States criteria would be eligible for inspection. In the former case, we would propose that 20 per cent of all events located by the system would be subject to inspection; in the latter case we would propose that 30 per cent of unidentified events be inspected. On the basis of the best estimates provided by United States scientists, and assuming the existence of control posts initially only on the territories of the three original parties, it appears that either formula applied to events of magnitude 4.75 or greater would result in about twenty inspections in the Soviet Union in the average year. At this point I should perhaps interpolate that our scientists believe that, roughly speaking, about 100 seismic events above a threshold of magnitude 4.75 are likely to occur each year in the area of the Soviet Union, and that about seventy of them are likely to remain unidentified by the original control net. Again speaking very roughly, we believe that the number of comparable events occurring on the territories of the United States and the United Kingdom, taken together, would be approximately the same. Once more I wish to make clear that the choice of which events were to be inspected from among those eligible would not, of course, be subject to any veto by the party on whose territory the inspection were to take place. This choice would be left to the other side.

(Mr. Wadsworth, United States)

My Government finds no logic in the assumption that because a completely comprehensive agreement is, for the moment, technically unfeasible there should be no agreement at all. We believe that this new approach offers us a way to achieve a workable agreement, despite the existing disagreements regarding both the capabilities of the Geneva system for the detection and identification of underground events in the lower yield ranges and the equivalent kiloton yields of events of a given seismic magnitude. It is our sincere hope that our colleagues at this table will see in this phased approach, as we do, the possibility of moving as rapidly as is technically feasible toward a comprehensive cessation of nuclear weapon tests, through continually lowering the threshold as scientific research provides new and stronger tools for detection and identification.

The CHAIRMAN (United Kingdom): We have just heard an important statement by the United States representative and, speaking as Chairman, I would ask the Soviet representative whether he wishes to comment now on the proposals which Mr. Wadsworth has put forward.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): I have a few questions which I would like to put to the United States representative in order to have a clearer idea of the substance of the United States proposal. We are all the more anxious to clarify what the United States representative called a new approach or new proposal for as I was listening to what he said much of it seemed to me familiar from previous statements he had made on this subject. Therefore, in order to find out if there is anything new, I would like to put a few questions.

My first is, does this new United States proposal mean that the United States proposes to exclude from the treaty which we are preparing a specific category of nuclear and hydrogen weapon tests, that is to say, the category which covers explosions of a magnitude below 4.75, and does it mean that such explosions would not be prohibited by the treaty -- in other words, that they would not in general be subject to any kind of regulation?

Secondly, is it intended that, in the case of explosions which will be below the threshold proposed in the new United States proposal, there will be a moratorium declared, that is to say, in the sense that, as long as the question

(Mr. Tsarapkin, USSR)

of control over explosions below a certain threshold is not regulated or agreed, such explosions also will be prohibited, that is to say, there will be a moratorium for them, as there was hitherto in respect of other explosions?

To these two questions — later, perhaps, I may have others — I would like to hear the United States representative's reply.

Mr. WADSWORTH (United States of America): The answer to the first question is that tests in the underground environment lower than the seismic magnitude 4.75 would be excluded from the first phase of our proposal.

The answer to the second question is that under the United States proposal there would be no provision in the treaty for a moratorium. The moratorium which has been in effect over the past year and several months is one which is unilateral and voluntary in nature, and the United States does not propose to include such a procedure in the treaty. The position of the United States as to a moratorium will remain exactly as it is today; it is reflected in President Eisenhower's statement of 29 December 1959 when he said:

> "Although we consider ourselves free to resume nuclear weapon testing, we shall not resume nuclear weapons tests without announcing our intention in advance of any resumption".

That would be the situation as far as the United States is concerned unless, of course, there should be some change in attitude, which is not now known to my delegation, later in the normal course of events. This is the position we take today. The proposal which I have made would leave the United States in the same position after the treaty had been signed.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): I understand therefore that your new proposal offers every opportunity for resuming nuclear weapon tests at any time?

Mr. WADSWORTH (United States of America): The answer is that under the new United States proposal, if we should agree upon a treaty, all three of us would be free — or could consider ourselves to be free — to test in the lower ranges.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): In this respect the United States proposal is aimed at reverting to the situation which existed in the world when nuclear weapon tests were being carried out in the United States, in the United Kingdom and in the USSR. Can I interpret it in that way?

Mr. WADSWORTH (United States of America): I can only repeat what I have already said, namely, that the United States would consider itself free to resume tests in the event that it considered this to be necessary for its national security.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): I should like to have some clarification in regard to the following. I need this not in order to dispute your proposals, because, as you will see hereafter, they cannot serve as a basis for any agreement, but simply in order that I can report your proposal more or less correctly to my Government. You talked about a threshold. How is that threshold to be understood? You said that an event of a magnitude of 4.75 was a threshold and that whatever was below that threshold would not be written into the treaty. Explosions below that magnitude may be carried out. Explosions of a higher magnitude will be regulated by the treaty. And who is going to define that magnitude and on what basis? I ask this question because, when the matter of magnitude was being discussed in December last year, our scientists assimilated the magnitude of, say, 4.75 to an explosion of a yield of about five kilotons, whereas the United States experts assimilated the same magnitude to the yield of an explosion of about nineteen kilotons, so even on this point there was a colossal discrepancy between the calculations of Soviet experts and the calculations of United States experts. The one side insisted that they were right and the other side that they were right. How do you propose to achieve agreement on the question of magnitude if, say, a magnitude were laid down in the treaty?

Mr. WADSWORTH (United States of America): It is my understanding that there was disagreement between the scientists in Technical Working Group 2 as to the translation of readings of seismic magnitude into estimated kiloton yields. That is the main reason why we have proposed that seismic magnitude be used as the

(Mr. Wadsworth, United States)

measuring standard. It is our opinion that the instrument readings could give us the magnitude, whereas we might not agree on the kiloton yield of a device which had given such readings. Thus, in our view, we would overcome the difficulty over translation by using the instrument readings on the commonly-accepted scale in seismology.

Mr. TSARAPKIN (Union of Soviet Socialist Republics): Because of your last statement, I should like to put another question.

(continued in Russian)

As far as I know, when the experts discussed the question of magnitude -- let us say, the Blanca explosion which had been carried out in the United States -- the Soviet experts equated it with a magnitude of 5.3, while the United States experts estimated the Blanca magnitude at 4.8. Therefore, the problem of magnitude readings is not one that is non-controversial for both sides.

Mr. WADSWORTH (United States of America): Not being a technician I am not competent to give my Soviet colleague a technical answer to his question. In this particular case the explosion to which he refers would be considered eligible. However, if the control system showed readings of a magnitude less than 4.75 the explosion would not be considered eligible for inspection. Of course, I do not know the differences in the magnitude readings at various distances from any incident, but I would imagine our experts in seismology would not have too much difficulty in averaging out the readings of the instruments in order to determine exactly what the seismic magnitude had been. As I say, I am not an expert and I reserve my right to answer this question more fully when I have been able to consult with the experts on my staff.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): What kind of control system do you envisage in your new proposal -- the complete control system as provided for and recommended by the experts in 1958 or another system?

Mr. WADSWORTH (United States of America): The control system would be as recommended by the experts in 1958, plus whatever improvements might be agreed upon between our scientists for immediate installation.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): The control system recommended by the experts in 1958 was based upon a fundamental postulate of principle, namely that all nuclear weapon tests would be prohibited in all environments: below the ground, in the atmosphere, at high altitudes and under the sea. Your new proposal prohibits only a fraction of underground explosions, which are above a certain magnitude, whereas underground explosions below a certain magnitude remain outside the treaty, which means that nuclear explosions will be resumed.

Are we correct in understanding that what you have in mind is the resumption of nuclear weapon tests under certain conditions, and that at the same time you consider that the whole control system as proposed by the experts in 1958 for the treaty prohibiting all nuclear weapon tests without any exception must be installed? I want you to confirm or deny that your new proposal aims at setting up the control system which was recommended for the treaty prohibiting all nuclear weapon tests but not at forbidding all tests by treaty; some tests are to be permitted. Do I understand correctly?

Mr. WADSWORTH (United States of America): That is correct as far as the proposal we have made is concerned. It will be remembered that in the last answer I made to Mr. Tsarapkin I said, "the control system ... plus whatever improvements might be agreed upon between our scientists..." (supra, page 12). Since it is well known that the control system, even in its initial phase, cannot be completed for some time, it is possible that we shall have approached the comprehensive treaty for which the control system was originally designed. It is certainly the hope of the United States, as Mr. Tsarapkin will find from reading the verbatim record of my initial intervention today, that the comprehensive treaty will be most rapidly approached, and that we shall lower the threshold as quickly as possible until the ideal of no threshold whatever has been attained. In the meantime, in order to make the identification system as efficient as we should like, we shall have to commence the construction of the entire system.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): I have one more question to put to the United States representative. I should like him to explain to me what was the United States Government's motive in submitting this new proposal which allows of the resumption of underground nuclear weapon tests, and which at the same time recommends the control system which was proposed in 1958 for a treaty prohibiting all nuclear weapon tests? Under your new proposal the treaty would have regulations covering all nuclear explosions of any magnitude in the atmosphere or under the water, all nuclear explosions carried out at high altitudes in outer space, and all nuclear explosions of a magnitude of 4.75 and above. But all these explosions in all these environments, including underground explosions of a magnitude of 4.75 and above, can be recorded by national recording stations, in the United States, the United Kingdom and the Soviet Union. No international control is needed for that. In these circumstances the Soviet Union can do without any international control, can do without establishing any control posts whatsoever on United States territory, and would be aware of every single one of the explosions which you will carry out in the United States, including underground explosions of a magnitude of 4.75 and above. For that we do not need a single control post on your territory.

In these circumstances, it would be interesting to know what is the meaning of your proposal for control, in view of the proposal which allows of underground explosions, as you are suggesting.

Mr. WADSWORTH (United States of America): I am afraid I do not quite understand the question. I would ask Mr. Tsarapkin to repeat it.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): The United States suggests in a new proposal the establishment of a control system as recommended by the experts in 1958. This control system was proposed for a treaty which would prohibit all nuclear weapon tests without any exceptions. And when the intention was to conclude a treaty prohibiting all nuclear weapon tests without any exceptions, the control system proposed by the experts in 1958 did have a meaning. It was justified because at that time it was not possible from our national territories alone to record all nuclear explosions, for instance small underground nuclear explosions. And it was for these underground explosions of small yield that the establishment of an international system with control posts on foreign territories was mainly required.

(Mr. Tsarapkin, USSR)

Now you propose not to include in the treaty small explosions of a magnitude of 4.75 and under. But what you propose to control does not require the establishment of an international system, because you propose to include in the treaty high-altitude explosions, explosions in the atmosphere and underwater explosions. All these explosions can be recorded by national stations, that is, the United States can record all explosions which, say, the Soviet Union might carry out on its territory in the atmosphere or under water; likewise the Soviet Union can record at its national stations all explosions which the United States might carry out in the atmosphere or under water.

As to underground explosions, you propose to prohibit only those underground explosions whose magnitude will be 4.75 and above. But these explosions can also be recorded by national stations. We in the Soviet Union, for example, do not need to set up control posts on your territory in order to record underground explosions of this magnitude. We will plot all these explosions from our national stations in our territory.

That is why the question arises: what is the purpose of an international control system if we, having our national network of control posts, shall have knowledge of all the explosions carried out in the world, which you are now proposing to include in the treaty? As for the purpose for which we previously intended to set up such a control system, you are now proposing that it should be dropped: you are proposing that small underground tests should be excluded. If they are not going to be included in the treaty, what is the sense of setting up an international control system when all those explosions which will remain in the treaty can quite readily be recorded by national stations? I think that you can now understand my question.

Mr. WADSWORTH (United States of America): I think I understand the Soviet representative's point but I doubt if it could be called a question. I tried to explain before that one has to look at all parts of this proposal together. First, because of what we consider to be a severe limitation on effective control of all underground explosions under the Geneva system, we feel that we must suggest this threshold of 4.75, above which the residue of unidentified events will be manageable, but those unidentified events must be detected by the same control system that we have been talking about from the outset.

(Mr. Wadsworth, United States)

Secondly, we propose a joint research programme in order to achieve a technological break-through and to wipe out the limitations which are seen by our scientists. We obviously could not do so well even on incidents above 4.75 if we did not use the Geneva system. When the time comes — as I am sure it must — at which the joint research programme will have overcome the technical difficulties, then you will have a comprehensive treaty and you will need the entire network. We therefore propose to start building the entire network.

Also, I think we should not forget that the United States proposes this in an attempt to overcome our difficulties, and not in an attempt to set the clock back — indeed we are attempting to set it forward. We are not proposing this in an effort to open a large field for additional testing or the resumption of testing; we are proposing it because we know that it will be impossible to obtain a fully ratified treaty if we cannot assure the proper authorities in the United States that the control which we have set up is in fact adequate.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): But what you have just said has not clarified anything, nor has it in the least done away with the reasons why we put that question to you. Although you say that underground explosions of a magnitude of 4.75 call for the setting up of an international network of control post points, we are of a different opinion. We consider that there is no need to establish control posts on other territories to register these explosions; national stations can register these explosions in any part of the globe, while explosions in other environments, for instance, in the air and under water, are still more likely to be registered by national stations. We therefore see no reason or justification for setting up an international control system within the limits outlined by you for the limited treaty you propose.

I have another question concerning your proposal to leave freedom of action to States in regard to carrying out underground explosions of a magnitude below 4.75. Are we to understand it as an invitation to other States to resume their work on improving nuclear weapons and carrying out tests of such weapons?

Mr. WADSWORTH (United States of America): As I understand that last question, our Soviet colleague asks if my proposal is that we all resume testing and weapon development. Is that the question?

Mr. TSARAPKIN (Union of Soviet Socialist Republics): Is this an invitation to other States to start nuclear explosions and to develop nuclear weapons?

Mr. WADSWORTH (United States of America): The answer to that question is a very definite "No". It is felt that a threshold of 4.75 would in fact be a deterrent to fourth, fifth or nth countries against starting a programme, because we believe that the smaller and more sophisticated devices which might be developed under our proposal would generally not be within the capability of countries which had not had experience in these matters. However, this is not my field. The answer is that we are definitely not trying to encourage anything. What we are trying to do is to get something started so that we can finally arrive at a comprehensive treaty.

I want to point out to my Soviet colleague that one of the main reasons why the United States has been able to make the proposal for a certain percentage of all located incidents -- or a certain percentage of all unidentified incidents -- which he will find in my statement, is that we have based our proposal on our ideas of the capability of the entire system, and not a system of national posts.

I would also indicate here that as far as high-altitude explosions are concerned it is the belief of our technicians that we need all the control posts of the Geneva system for that, also. We therefore do not believe that national systems can in fact detect all the explosions to which Mr. Tsarapkin referred in his argument. We think that the Soviet delegation persistently underestimates the extent of the control needed for any given system. In fact, that has been one of our difficulties from the very first day that we met here. We must recognize that we do have differences in this regard and, as I said on 12 January, we must exercise all the ingenuity of which we are capable to try to get round the situation. So far as I know, national stations do not exist for the purpose of identifying an incident as a nuclear explosion. They exist in order to register certain earth tremors, which of course generally are, and will continue to be, earthquakes; but they do not identify an earthquake as an earthquake except under rather extraordinary conditions in which the seismic magnitude would indeed be very high.

Therefore, although I quite understand that our Soviet colleague is not happy about the idea of anything less than a comprehensive treaty, I ask him to consider the realities of this matter.

The CHAIRMAN (United Kingdom): We have listened to an important statement by the United States representative and to certain questions put by the Soviet representative with the object, if I understood him rightly, of securing elucidation and clarification of what our United States colleague said to us. I should now like to make some preliminary comments on behalf of the United Kingdom.

When we resumed our Conference a month ago, on 12 January, it was clearly recognized by all three delegations that the main task now facing the participants in the Conference would be to find a way out of the very serious difficulty revealed by our Technical Working Group 2 in the sphere of underground controls. The United States representative has now made a proposal which is the result of his Government's studies on this matter. My Government has also been giving most careful study to the problem.

The main considerations which have guided the United Kingdom Government in this study are as follows. The declared aim of the United Kingdom at this Conference is to achieve, by international agreement, the permanent discontinuance of all nuclear weapon tests under adequate international control. This aim remains unchanged, and it has been our point of departure in considering this problem of underground tests just as with any other aspect of the treaty. The general principle which has guided, and still guides, United Kingdom policy was stated by Mr. Ormsby-Gore at our thirty-seventh meeting on 19 January 1959 when we agreed, in company with the United States, to forgo any formal link between a nuclear tests treaty and the progress of disarmament. I quote from his remarks:

> "We are prepared, therefore, in principle to accept the discontinuance of nuclear weapons tests indefinitely subject only to the effective fulfilment of the treaty itself, both as regards the obligation not to conduct tests and as regards the progressive establishment of an effective system of international control over that obligation". (GEN/DNT/PV.37, page 9)

Two considerations are contained in this principle. We are prepared to enter into an obligation to discontinue nuclear weapon tests indefinitely provided we are assured that this obligation will be carried out by others; and, of course, we can have this assurance only if we can foresee the progressive establishment of an effective system of international control.

(The Chairman, United Kingdom)

Now, the underground problem, in a nutshell, is that we cannot for the time being foresee with certainty the progressive establishment of an effective system of international control over all underground testing. The reasons for this are technical, and in assessing the technical situation with regard to underground controls my Government has naturally relied primarily upon the views of the United Kingdom team in Technical Working Group 2, under Sir William Penney.

We have had to consider four particular points which emerged from the Working Group and from the statement by the United Kingdom experts annexed to its report. First, in the words of the United Kingdom experts, the new seismic data from the Hardtack series of underground tests have shown that the 1958 experts' report was too optimistic in its estimate of the value of first-motion as a criterion for the identification of earthquakes (GEN/DNT/TWG.2/9/Annex III, page 1).

Secondly, and as a direct consequence of the first point, the United Kingdom experts concluded that it was not possible at the present time to construct criteria which would identify a large proportion of earthquakes as such. They wrote:

> "In our opinion, the best that can be done in the present state of knowledge is to define criteria which will identify a modest proportion of earthquakes. The remaining events must be regarded as eligible for inspection, even though the number of events will, for a few years, be far too large for all to be inspected". (Ibid., page 3)

The United Kingdom experts also recognized — although their annex does not explicitly state this — that identification was much more difficult for events of small magnitude than for events of large magnitude. This means that most of the events which in the present state of knowledge could be identified would be the larger seismic events. So we may restate the second point in the following way: Criteria available at the present time will permit identification of only a modest proportion of earthquakes, and the majority of those identified will be in the larger magnitude ranges.

The third point which we have taken into account is that, to quote again the words of the United Kingdom experts:

> "...world research on seismology, including work done by the control organ itself, could in a few years materially increase the proportion of earthquakes which can be identified". (Ibid.)

(The Chairman, United Kingdom)

Thus, although adequate control in the lower magnitude ranges cannot at present be guaranteed there seems good reason to hope that experience and energetic research would improve the situation in a few years. We recognize that this is an argument for setting up the control system as soon as possible, because the existence of control posts will greatly and rapidly increase the flow of useful data.

The fourth point that we have had to consider is that, whereas the United Kingdom and United States experts presented reports in broad agreement with each other, the Soviet experts did not agree with either of them as regards the significance of the new seismic data or as regards criteria, but only as regards possible improvements to the system. This last was the only point on which all the experts were agreed. Thus the three participants in this Conference have no common technical understanding of the problems existing in the underground environment, no agreed criteria for inspection, and no common assessment of the capabilities in the underground environment of the control system outlined by the experts in 1958. Not only does this lack of agreement make our political task in this Conference more difficult; it also makes the future development of any control system more uncertain and problematical.

Our consideration of these four points has led us inescapably to the conclusion that, as regards the lower magnitude ranges of underground events, there does not as yet exist that assurance of the progressive establishment of an effective system of international control which would justify immediately a permanent obligation for the discontinuance of nuclear weapon tests in this particular area. Such a permanent obligation would be certain; but the prospects of effective control are still uncertain. These prospects are hopeful, but by no means certain, especially given the basic technical disagreement which now exists. Thus, the uncertainty of control would not match the certainty of the obligation, and the guiding principle which I have recalled earlier would not be satisfied.

This is the conclusion to which study of the results of Technical Working Group 2 has led my Government. I must state with all possible emphasis that we do not think it need in any way alter our general aim of a permanent discontinuance of all nuclear weapon tests in all environments and for all time under adequate control. We still have every hope of achieving that aim in due course. But the facts I have stated have forced us to the further conclusion

(The Chairman, United Kingdom)

that some alteration in the approach to that aim is now inevitable. I would stress that it is purely the facts of the technical situation which have led us to conclude, regretfully, that a staged or phased approach to the permanent discontinuance of all underground tests is now necessary. The prime reason is that the experts in 1958 were working with insufficient data, and that the data acquired since then have unfortunately but inescapably shown that their conclusions with respect to this one area of underground controls were too optimistic. This, as I have said, is a matter of technical facts, and on the basis of existing knowledge the facts would still be the same even if a greater measure of agreement had been reached in the Technical Working Group. Of course, if greater agreement had been reached we could perhaps deal with the situation with more confidence. But the situation itself would not be materially altered. Only improved knowledge and improved techniques can alter it.

The essence of a phased approach is of course that the scope and nature of the treaty obligation to discontinue testing should be in accordance, at each stage, with the availability of agreed and adequate controls. The one should develop pari passu with the other. Where we can see adequate controls available, or a sufficiently certain prospect of them, there we can extend the indefinite, permanent, discontinuance of testing.

The proposals just put forward by the United States representative on behalf of his Government are, he has indicated, intended to give practical expression to this principle as regards the underground environment. I shall not attempt to follow my United States colleague into the details of his proposal. In fact, as I have said before, my Government, having conducted no underground tests or acquired any original data from such tests, is not fully equipped to deal with all the technical aspects of such a proposal. Nevertheless, we have had the advantage — I think I might say that all of us have had the advantage — of some advance notice of the United States proposals. I am able to say that my delegation believes that the threshold described by the United States representative represents a fair estimate of the boundary or limit down to which there is a reasonable certainty of adequate control on the basis of the control system described by the experts in 1958 and discussed by us at this Conference. We believe that below this limit there is not at present the assurance of adequate control.

(The Chairman, United Kingdom)

At the same time we can join most warmly in the hopes expressed by the United States delegation that it will in due course prove possible to extend adequate control progressively below this limit if the necessary effort is put into research aimed at improving techniques, instrumentation and criteria. I can say that my Government accepts the invitation to join in such research, within the limit of our resources, and had indeed already resolved to do all it could in this direction. The agreed portion of the Technical Working Group's report has pointed out some lines which such research could profitably follow. We believe that no time should be lost in pursuing research in those directions and any others that may appear promising.

The proposal which the United States representative has laid before us would be that the treaty ban on underground tests down to the proposed threshold, with the control arrangements proposed for this ban in terms of techniques, criteria, and so on, would represent simply a first stage, and we hope a temporary stage. In the questions, or some of them, which the Soviet representative addressed to our United States colleague, he appeared to be under the impression that it might represent not a first and temporary stage but a final stage, and I hope that, on reading the verbatim record and appreciating that such is not the intention of this proposal, he will realize that much of the doubt which underlies his questions is unfounded. Now, as joint research got under way, and as the establishment of the control system intensified the collection of data, we should hope to see an improvement of techniques and criteria that would allow of the progressive lowering of the threshold until the conditions were fulfilled for a permanent obligation to discontinue all underground testing without exception. Let me recall here, in passing, that our Soviet colleague seemed a little while ago to show a considerable interest in the idea that any criteria initially incorporated in a treaty might be temporary and subject to revision when improvements in techniques and instrumentation were achieved. It seems to me that the United States proposal would allow of this.

We agree with the United States that the definition of the threshold in terms of seismic magnitude rather than of kiloton yield would have a considerable advantage in enabling us to side-step for the time being one complex area of disagreement revealed in the Technical Working Group. If thereby we can hasten our work and advance the conclusion of a treaty and the establishment of the control system, with all the impetus that this would give to a programme of research, that would be an important benefit.

(The Chairman, United Kingdom)

Further, we note that the United States proposals include an acceptance of the quota principle for conducting on-site inspections. We welcome this, because it means that all three delegations are now basing themselves on this principle, which should considerably ease our task in settling the inspection problem.

To conclude, my delegation considers that the proposal for a phased threshold in the underground environment, now put forward by the United States, is one which is consistent with the facts of the existing technical situation; and we believe that this approach offers every hope of arriving at the ultimate goal of a permanent discontinuance of all tests under effective control. We are ready to join in exploring a treaty solution incorporating this proposal and it is our hope that the Soviet Union will agree to do the same. Our great desire is to move rapidly ahead so that the large measure of agreement already reached at this Conference can be given treaty force, and so that an intensive effort of research can be developed without delay in order to dispel the uncertainties remaining in this area of underground tests.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): I have a further question, Mr. Chairman, because I had not finished putting questions when you made your statement.

This is the question. The United States representative has replied in the negative to my question whether the new United States proposal is not an invitation to other States to follow the example of the United States and to start making and improving their nuclear weapons. Mr. Wadsworth replied with alacrity and with great willingness: no, his answer was in the negative, and he motivated this by the fact that it would be technically difficult for other States to make and test nuclear weapons of such low yield. This argument seemed to us interesting from the point of view that the United States would appear to be striving to gain for itself some kind of military advantage in proposing the resumption of underground nuclear weapon tests, namely to give an opportunity of carrying out tests only to itself, the United States, because it considers that it will be difficult from the technical standpoint for other States to make weapons of such low yield. Would it be correct to understand those to be the true motives of the United States in this approach?

Mr. WADSWORTH (United States of America): I am afraid I do not completely understand the question, but I shall try to answer it.

In the first place, in making this proposal the United States is not encouraging anyone to follow an example of the further development of weapons. The United States has never said that it will resume testing. The United States is merely trying to get a treaty that can be adequately controlled.

In the second place, military advantage certainly relates to the question of control and, since our motive is the greatest possible effective control, we are naturally against anyone's gaining any military advantage.

I think we ought to agree that the important idea here is that of phasing. If, as the representative of the United Kingdom has said, we were suggesting a treaty which would never move from this first phase, that would be one thing. However, we are ourselves proposing joint research programmes whereby we have every hope that the threshold can be quickly and very greatly reduced so that we can then move into a second and perhaps a third phase which will enable us to achieve a comprehensive treaty. That is the thing which should be remembered, rather than the question of whether somebody else is going to be encouraged to do something that we ourselves may never do.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): One aspect of the matter is still not clear to us. We have one more question.

It follows from the replies of the United States representative, and particularly from what he has just said about the United States never having stated that it would resume tests, that his statement differs from the one which President Eisenhower made on 29 December when he said quite plainly that the United States undertook merely to announce beforehand -- a few days, I do not know how many, he did not say -- when it is about to resume tests. So much we know: you will resume tests. Only when you resume them you will make an announcement in the Press. We shall learn about your forthcoming tests from the newspapers three or four or fourteen days beforehand. But the fact that you are going to carry out tests is perfectly clear from President Eisenhower's statement. So we cannot possibly agree with your assertion, Mr. Wadsworth, that the United

(Mr. Tsarapkin, USSR)

States has never stated that it will resume tests. The United States has already stated that it will resume tests. But at the same time it has announced that all the world will be warned beforehand of the time when tests will be resumed. Well, then, we shall wait and see.

I should now like to ask another question. How can the United States proposal of today that a prohibition of nuclear explosions of a yield below a certain threshold should not be written into the treaty — which amounts in fact to a resumption of tests — be compatible with the resolutions adopted by the General Assembly of the United Nations at its fourteenth session concerning the cessation of atomic weapon tests, for which, among others, the United States, the United Kingdom and the Soviet Union cast affirmative votes and which call on the nuclear Powers not to resume atomic weapon tests and to expedite the conclusion of a comprehensive treaty for a ban on tests? Do you consider your new proposal to be compatible with those resolutions of the General Assembly for which you voted?

Mr. WADSWORTH (United States of America): There is nothing in any official announcement by the United States which anyone can construe as declaring that the United States is going to resume testing. The language of President Eisenhower's statement of 29 December 1959, "Although we consider ourselves free to resume", certainly does not announce any intention to resume. Some countries have indicated unilaterally that they will refrain from testing as long as others do so or will refrain from testing as long as useful talks continue in Geneva. That is a unilateral decision as to what is best for the national security of the country itself.

It is true, of course — and I am personally proud — that the United States voted in favour of the United Nations resolution calling upon the nuclear nations to refrain from testing. The United States has done nothing whatever to violate that resolution and the United States has never said that it intends to violate that resolution. Therefore, there is no inconsistency as I see it, and there is no inconsistency as the Government of the United States sees it.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): At present I should like to make only a few brief remarks on today's United States proposal. While reserving, of course, the right to make a more extensive statement of our position, I should like to make some comments of principle on our position in regard to this proposal.

The proposal put forward today by the United States delegation for the consideration of the Conference to leave out of the treaty on the prohibition of nuclear weapon tests all underground tests of a magnitude below 4.75 actually amounts to authorization to resume nuclear weapon tests. Everyone realizes that if the new United States proposal is adopted the treaty on the cessation of nuclear weapon tests will lose all meaning, for there will in fact be no cessation of tests. If the new United States proposal is adopted it will preserve and even legalize the possibility of continuing the nuclear arms race, of improving various types of nuclear weapons by underground testing.

It is clear from the Press and from the report of the United States Atomic Energy Commission that a whole series of new types of nuclear weapons of various yields and for various purposes have been prepared and are now ready for testing. Those who are concerned with the production of nuclear weapons in the United States are ready to begin test explosions at any moment and are only waiting for the starting signal to carry out these explosions of nuclear weapons.

The treaty must provide for the cessation of all tests, all explosions, of all types of nuclear weapons: underground, in the air, under water, at high altitudes, in outer space. Any government which is the first to start testing nuclear weapons would be assuming a heavy responsibility before the nations. No one should have any illusions concerning the situation which would arise in the world if any State resumed the testing of nuclear weapons. The consequences of such a step would be disastrous. Other States possessing the same weapons will be compelled to follow a similar course and those which do not possess these weapons will, when they see that their hopes for the cessation of nuclear weapon tests everywhere in the world have not been justified, begin to produce their own weapons, and there are States possessing sufficient productive, scientific and technical resources which have already stated more than once that they would work in that direction.

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If the United States were to resume nuclear weapon tests, by that very fact an impulse would be given to the resumption of an utterly unrestricted nuclear arms race in testing weapons of any yield and in any environment.

During his last statement, the United States representative said that other States would find it technically difficult to produce nuclear weapons of small yield to be tested underground. This statement is noteworthy from the following point of view. The statement shows that the United States, or the United States War Department, who are the manufacturers of nuclear weapons in the United States, require underground explosions for the purpose of improving certain types of weapons. But we should not forget that there are other States to be considered, and if the United States, which has introduced the proposal that the treaty should not deal with nuclear underground explosions below a certain threshold, begins underground nuclear weapon tests, other States may in that case prefer to carry out different tests, by different means, in different environments, and of a different yield, which will meet the requirements of their military programmes and their own concepts of national security. Perhaps this would not fit in with the United States military programme. It so happens that the United States has its own programme for the development of nuclear weapons, while other States have programmes of their own for the development of their own nuclear weapons. You have your plans, namely underground tests, but other States have their own plans for testing nuclear weapons by other means, using the most up-to-date scientific and technical discoveries in this regard. What your proposals for the resumption of nuclear weapon tests will lead to we do not know, nor whose will be the biggest headache in the end. Therefore the wisest course to follow from the national point of view, the only correct course, would be to maintain that good relationship which has been brought about in the world — the actual cessation of tests — and not to resume nuclear weapon tests but to strive at all costs to prevent a renewal of the nuclear arms race, to prevent the resumption of nuclear weapon tests, because the resumption of such tests will bring no good to anybody. Of course we cannot possibly agree that the treaty on which we are working should actually sanction the resumption of nuclear weapon tests. Here the principle is important, because you cannot confine nuclear weapon tests within some sort of limits. If you reject the principle of discontinuing nuclear weapon tests, then everyone will start testing nuclear

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weapons of such a yield, in such conditions and with such resources as are convenient to them and which they consider it necessary to develop. It suffices to raise this simple question to show up in a proper light the prospect with which the peoples will be faced in the event of the United States resuming nuclear weapon tests.

I should like to make one more comment. We are surprised that the United States, which is well aware both of the utter uselessness, or rather, the harmfulness of a treaty which would leave an opportunity for the resumption of nuclear weapon tests, and of the negative attitude of the Soviet Union to such a limited treaty which would put back the existing position to the point in time when the whole world shuddered at the experimental explosions of nuclear weapons -- we are surprised, I repeat, that the United States, knowing this, could at the same time decide to put forward this absolutely unacceptable proposal, which cannot serve as a basis for any kind of agreement.

I should like to warn you once again that if the United States insists on its proposal and matters reach the point where nuclear tests are resumed on the initiative of the United States, in that case no one can compel other States to remain in the position in which they have been hitherto. Then a general, utterly unrestricted arms race will begin in the field of nuclear weapons and, as I have already said, the thundering crashes of nuclear explosions of any yield, in any environment and by any means will be renewed in the world. That will lead to no good.

We shall, of course, carefully study the statement made by the United States representative at today's meeting. We shall have further questions to ask. We shall prepare them and we shall prepare a further statement as well. This is our preliminary statement, but it reflects our position of principle in regard to this subject.

The CHAIRMAN (United Kingdom): Speaking as Chairman, I would say that all three delegations may wish now to reflect upon the statements which have been made today and not to carry our discussions further at this stage. That being so, we shall pass to the communique.

After an exchange of views the Conference decided to issue the following communique:

"The one hundred and seventieth meeting of the Conference on the Discontinuance of Nuclear Weapon Tests was held at the Palais des Nations in Geneva on 11 February 1960 under the chairmanship of the representative of the United Kingdom.

"The United States delegation made a statement to the Conference containing proposals for a phased treaty.

"The next meeting of the Conference will be held on Friday, 12 February 1960, at 3 p.m."

The meeting rose at 6 p.m.

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CONFERENCE ON THE DISCONTINUANCE OF NUCLEAR WEAPON TESTS

Official Records

Saturday, 19 March 1960, at 10 a.m.
Palais des Nations, Geneva.

VERBATIM RECORD OF THE ONE HUNDRED AND EIGHTY-EIGHTH PLENARY MEETING

Chairman: Mr. ORMSBY-GORE (United Kingdom)

LIST OF MEMBERS OF DELEGATIONS PRESENT AT THE TABLE

United Kingdom:	Mr. D. ORMSBY-GORE
	Sir Michael WRIGHT
	Mr. H.T. MORGAN
	Dr. F. PANTON
Union of Soviet Socialist Republics:	Mr. S.K. TSARAPKIN
	Mr. A.I. USTYUMENKO
	Mr. I.G. USACHEV
	Mr. O.A. GRINEVSKY
United States of America:	Mr. J.J. WADSWORTH
	Mr. D. POPPER
	Dr. C. WALSKE
	Mr. D. MARK
	Mr. D. MORRIS
Representative of the Secretary-General:	Mr. T.G. NARAYANAN

The CHAIRMAN (United Kingdom): I declare open the one hundred and eighty-eighth meeting of the Conference.

Perhaps before we start I might just say what a privilege and, indeed, what a pleasure it is to find myself once again at this Conference table. I have been absent from these meetings, I know, for some time now, but absent only in body, not in spirit: I have been watching your patient work in attempting to reach an agreement on this important subject.

Does anyone wish to speak?

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): We are all happy to welcome you, Mr. Ormsby-Gore, at our meeting today. You are a rare visitor among us. Today, on the instructions of the Soviet Government, I should like to make the following statement and put forward a proposal.

It will soon be eighteen months since negotiations began in Geneva between the Soviet Union, the United States of America and the United Kingdom on the cessation of nuclear weapon tests. The peoples of the world are expressing their concern at the incredibly slow rate of progress in the Geneva negotiations. They are justifiably alarmed by the fact that the aim assigned to those negotiations has not yet been achieved: no treaty on the discontinuance for ever of all atom and hydrogen weapon tests has been concluded. This alarm has become particularly strong of late, since a real danger of the resumption of nuclear weapon tests has arisen in connexion with the statement made by the President of the United States on 29 December 1959 concerning the refusal of the United States Government to prolong the moratorium on nuclear explosions.

Concern and surprise are bound to result from the fact that this step has been taken by the United States just when, notwithstanding the difficulties that have repeatedly been created by the Western Powers during the negotiations, definite and not inconsiderable positive results have already been achieved at the Geneva Conference: agreement has been reached on the preamble to the treaty and on seventeen of its articles. Agreement has also been reached on the text of the annex relating to the preparatory commission. Thus a significant part of the text of the treaty has been agreed. Although some important questions still remain unsettled, there is no denying that at the Geneva Conference, where the

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Soviet Union has recently put forward new proposals, there are prospects of a further narrowing of the gap between the positions in regard to a number of contentious points, and ways have been opened for a mutually acceptable settlement of outstanding questions. This gives us reason to hope that we shall succeed in signing a treaty in the near future, and this would be a first practical step towards ending the nuclear arms race and banning these weapons of mass destruction. These hopes are all the more justified because the question of discontinuing nuclear weapon tests relates to a number of fairly simple, non-complicated disarmament questions, since an agreement to discontinue nuclear weapon tests would not by itself entail either a reduction of armed forces and armaments or their elimination. This question is simple and uncomplicated because its solution does not require any complicated negotiations for the reduction or elimination of armed forces and the establishment of control over the implementation of these measures. The essence of this question at the present time is that the situation which has arisen in the world since November 1958, when the Powers possessing nuclear weapons stopped testing them, should be consolidated and given a legal form in a treaty providing for the prohibition for all time of all atom and hydrogen weapon tests and for the establishment of international control over its observance.

The peoples of the world expected that after the resumption of negotiations in Geneva on 12 January the participants in these talks would take steps to expedite the settlement of outstanding questions so that a comprehensive treaty on the prohibition of nuclear weapon tests would be signed in the immediate future. Unfortunately, however, after the recess the state of affairs at the Geneva Conference took a turn for the worse. The United States clearly took the course of retreating from a comprehensive treaty which would ban all atom and hydrogen weapon tests for all time without any reservations or conditions whatsoever. The United States is trying to bring about the conclusion of a limited treaty, that is, a treaty which would leave the nuclear Powers free to carry out nuclear weapon tests underground.

The United States began to prepare this official position of theirs as far back as last April, when President Eisenhower in his message to Mr. Khrushchov put forward the idea of concluding a limited treaty, that is, to approach the problem of prohibiting nuclear weapon tests in phases. This proposal was then

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put forward by the United States delegation at the Geneva Conference. Shortly afterwards it became known that the United States was actively preparing to resume the underground testing of nuclear weapons.

Recently a report appeared in the United States Press stating that at the beginning of January United States military and civilian specialist scientists had been given instructions to prepare for a new series of underground nuclear explosions in Nevada. It was reported in the Press that these nuclear explosions would be carried out between May and July next. Two days ago it became known from a statement made by Senator Anderson and by the United States Atomic Energy Commission that in January 1961 the United States Atomic Energy Commission would carry out a nuclear explosion in the Salado saltmines in the State of New Mexico.

It is no secret that these steps result from the activities of those forces in the United States which are trying to prevent an agreement from being reached, and which from the very outset of the Geneva talks took steps to represent to the outside world that it was impossible, or extremely difficult, to establish effective control over underground nuclear explosions, and then, by referring to the technical difficulties, to justify their refusal to agree to prohibition of underground nuclear weapon tests.

The tendentious nature, exaggerated appraisal and, at times, incorrectness of the assertions advanced by certain United States experts regarding the difficulty of control over underground explosions were shown up with sufficient cogency by the Soviet experts during the scientific and technical discussions that took place in Geneva last November and December.

Such intensive stressing by the United States side of the difficulties of control appears all the more unconvincing since much has already been done in the course of the negotiations at Geneva to improve and increase the effectiveness of the control system. Everyone knows that the recent meetings of experts from the Soviet Union, the United States and the United Kingdom, held at Geneva in December last, adopted an agreed conclusion "regarding possible improvements of techniques and instrumentation ... which have the purpose of improving the detection and identification of seismic events" (GEN/DNT/TWO.2/9, page 3). This conclusion contains a number of recommendations amplifying the recommendations submitted by the experts in 1958.

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But the process of improving the control system does not stop there. That is only the beginning. Thereafter, in the light of operational experience of the control system, its methods of detection and identification of nuclear explosions and its instruments and equipment will be periodically reviewed with due regard to scientific and technical progress in those fields.

In this connexion there already exists an article, agreed at the Geneva Conference, providing for the introduction of improvements in the control system two years after the entry into force of the treaty, and thereafter for annual review of the system.

Furthermore, agreement has been reached between the representatives of the Union of Soviet Socialist Republics, the United States of America and the United Kingdom at the Geneva Conference on a provision authorizing the control commission to undertake measures for the organization of scientific research work with a view to further improvement of the control system.

All these articles and provisions of the treaty already agreed between the three nuclear Powers at the Geneva Conference, with the experts' recommendations, open up wide possibilities for making all-round, general improvements in the control system and, in particular, for improving its effectiveness specifically in respect of underground nuclear explosions.

The question arises, what more does the United States want?

If the already-adopted provisions of the treaty ensuring the organization of an efficient and effective control system, if the agreed measures for the future aimed at further improving that system and making it still more effective, do not satisfy the United States, then it is clear to everyone that the position of the United States is certainly not based on its concern for improving the effectiveness of the control system. If that were really the point at issue, then the measures listed above would be entirely adequate to ensure this.

The opponents of an agreement on the cessation of atomic and hydrogen weapon tests make no secret of the fact that for purely military reasons the United States does not wish to bind itself with any commitments in regard to discontinuing all nuclear weapon tests. These circles are searching hard for a specious pretext which they could use as a scientific and technical justification, or rather as a cloak, for their desire to retain a free hand to resume nuclear tests. This and this alone is why the negotiations at Geneva have already lasted seventeen

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months and the drafting of the text of the treaty is not yet completed, nor the treaty signed. References to allegedly incomplete technical methods of detecting and identifying nuclear explosions are obviously being used in order to resume nuclear explosions underground under the cloak of this technical jargon.

The United States is trying to avoid the preparation of a comprehensive treaty on the cessation of nuclear weapon tests, and is creating new difficulties in the negotiations and screening itself with references to new circumstances. Now, under the pretext that some United States experts are expressing doubts about the adequacy and effectiveness of control over underground nuclear explosions, the United States has again started to insist that the treaty on the prohibition of nuclear weapon tests should not extend to experimental explosions of nuclear weapons underground, and has already formally put forward a proposal that underground nuclear explosions of a seismic magnitude of 4.75 and under should not be prohibited by the treaty in the first stage.

One cannot fail to see that this proposal of the United States represents a retrograde move and a very dangerous one. Its danger is that it is designed to prohibit not all nuclear weapon tests but only some. Under this United States proposal underground nuclear weapon tests below the magnitude threshold specified by the United States will not be prohibited by the treaty. If it were accepted, it would be a manifest invitation to resume underground nuclear weapon tests.

In this question, however, it is the principle which matters -- the treaty must be comprehensive without any exceptions or reservations, otherwise it will have no meaning and will not achieve the purpose for which it is intended.

Agreement on the cessation of all nuclear weapon tests would be a dam barring the way to the further development and spread of nuclear weapons, and would deliver mankind from the terrible threat associated with this dangerous sequence of events. For this reason the treaty on the cessation of nuclear weapon tests should provide for the prohibition of all atomic and hydrogen weapon tests for all time, without exception. No loophole should be left in this treaty for any kind of nuclear weapon tests.

No one should be under any illusion in regard to the fact that, if one nuclear Power takes the initiative and resumes the testing of nuclear weapons, other nuclear Powers will naturally be obliged to follow suit. The dam will be destroyed, and then it will be impossible to contain the testing of nuclear

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weapons within any limits. Other Powers will consider themselves free to resume atom and hydrogen weapon tests in such numbers, of such magnitude and under such conditions as would correspond to their own concept of security and accord with their own plans and programmes for the development of nuclear weapons.

Everyone realizes that the resumption of nuclear weapon tests will lead to a resumption, in an even more intense form, of the nuclear arms race. Research and construction will be carried out on a wide scale in order to create new and even more destructive and powerful types of nuclear weapons — weapons of mass destruction. Once tests are resumed, no one will be able to restrict or limit either the conditions under which nuclear explosions will be carried out, or their magnitude, or their numbers.

The situation may be further complicated to the highest degree by the fact that other States which are technically the most developed, which possess the necessary level of scientific and technical development and a large industrial potential, may try to take advantage of the resumption of atom and hydrogen weapon tests by the nuclear Powers and may also enter this race and take steps to make their own nuclear weapons, which would increase still further the danger of a nuclear war of annihilation and would, of course, bring to nought the possibility of the agreement on which we are working here.

Such a turn of events is entirely possible once the United States resumes nuclear tests and so disturbs the situation which now exists and which is characterized by the complete cessation of nuclear weapon tests on the part of the three nuclear Powers -- the United States, the Soviet Union and the United Kingdom.

All those considerations show most convincingly that agreement on this question can be of value only if the treaty provides for a complete ban on all nuclear weapon tests for all time, without any limitations, conditions or reservations.

The Governments of the nuclear Powers bear a tremendous responsibility, not only to the peoples of their countries but also to the whole of mankind, in regard to experimental explosions of nuclear weapons. There may, of course, exist in one country or another different views, among scientific experts as among statesmen, both on the technical evaluation of questions connected with

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the cessation of nuclear weapon tests and on its political consequences. Given the wish, it is always possible to find scientific experts or statesmen who will express doubts concerning the degree of effectiveness of control or concerning the wisdom of such a step as the cessation of tests, and who on the basis of those doubts propose the resumption of nuclear weapon tests.

In this connexion we might mention Dr. Teller and those United States experts who are connected with the production, development and improvement of atom and hydrogen weapons. These militarist scientists, whose material prosperity is linked with the further development and improvement of nuclear weapons, are untiring in their ingenuity and direct their evil genius, their ill-will towards preventing agreement on the complete prohibition of all nuclear weapon tests.

The well-known United States social leader and important industrialist Cyrus Eaton, writing at the end of February in a letter to the editor of the newspaper Cleveland Plain Dealer, spoke aptly about the harmful influence of the United States military authorities and militarist scientists — I quote from the letter:

> "There can be no hope whatever of an agreement at Geneva while pressure in favour of further, even if limited, tests continues to be successfully put on the White House and Congress by the United States Defense Ministry, the Atomic Energy Commission and a small handful of scientific advisers vitally interested in urging the United States to take the risk of further tests."

To take the advice of these scientists or generals or politicians who have adopted this position is not, however, the best way out of the situation. This advice, if accepted and put into effect, will lead to incalculable disasters for the whole of mankind.

It must not be forgotten that the nuclear Powers do not exist in a vacuum, isolated from others, but on one planet with other States; hence they must not remain deaf, they must not ignore the demands of other countries that nuclear weapon tests should not be resumed; they must not remain deaf to those countries' unanimous appeal to them to speed up the conclusion of a treaty on the cessation for ever of all atom and hydrogen weapon tests.

All the countries of Asia and Africa, regardless of their social structure and political sympathies, demand the complete cessation for ever of all nuclear weapon tests.

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The neutral countries are taking a decisive stand against the resumption of any kind of nuclear weapon tests. In this connexion I may refer to the statement made by the Foreign Minister of Sweden, Mr. Unden, on 29 February. He said that the agreement already prepared in broad outline at the Geneva Conference was in any event better than no agreement at all, and better for instance than an agreement which would leave the way open to underground nuclear weapon tests as would the United States proposal of 11 February. The Foreign Minister of Sweden stated:

> "What is necessary is not further technical study and lengthy discussions but a definite position and a political act of goodwill. We cannot admit that the demand for an agreement which would be perfect in every respect should be utilized in order to scuttle the attempts to find practical, workable solutions."

Even the Governments of some States members of NATO have taken an equally definite stand. I might quote by way of example a statement made in the House of Commons of Canada on 11 February by Prime Minister Diefenbaker and on 11 February by the Minister for Foreign Affairs, Mr. Green, Mr. Green stated:

> "We are against these tests and the stand we have adopted could be summed up as follows: that we are against any further nuclear tests in any country. We would vote in the same way whether the tests were United States or United Kingdom ... I can only state again that we are against tests regardless of whether the United States or the United Kingdom opposes this or not."

As you can see, the attitude of Canada — a member of NATO — is quite definitely against the resumption of nuclear tests.

The Governments of the nuclear Powers must make a political decision and without any further delay conclude a treaty on the prohibition for all time of all nuclear weapon tests together with the establishment of appropriate control. This is what the interests of their own peoples commit them to do; this is what all mankind expects of them with great impatience. An eloquent confirmation of this is the resolution adopted unanimously at its last session by the General Assembly of the United Nations, calling upon the nuclear Powers not to resume nuclear weapon tests and to speed up the conclusion of a treaty to this effect.

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The Soviet proposals (GEN/DNT/PV.148, pages 6-14) submitted to this Conference last December on the composition of the control commission, control post staffing and the voting procedure on budgetary and financial matters clear the way for the speedy completion of these negotiations and the drafting of the text of the treaty, if all the participants endeavour to reach agreement. Apart from the questions just mentioned, on which the Soviet Union has gone a long way to meet the position of the Western Powers, there remains one unsettled question — that of the inspection quota. The Soviet Government formally submitted its proposal on this question as far back as April last year. We believe that the question of inspection could and should be settled as a political question, independently of the contentious problem of the number of unidentified events. The originator of this solution to the inspection question was, as all know, the United Kingdom Prime Minister, Mr. Macmillan, who proposed it during his visit to Moscow in February last year. That is why, when making our proposal for the establishment of inspection quotas, we expected a speedy and positive reaction from the United States. However, the United States Government has not given its reply to this proposal for almost a whole year, and this question is still unsettled.

The Soviet Union has gone as far as possible to meet the position of the Western countries and has announced its readiness to agree to review of the inspection quota in accordance with the article (GEN/DNT/15/Add.5) adopted by the Conference which provides for a periodic review of the system. The first review of the quota could take place two years after the treaty enters into force, and subsequent reviews could take place annually.

There is one other question on which the Soviet Union has made an important concession to the Western countries. Because the conference of experts of our three countries, namely the USSR, the United States and the United Kingdom, which took place in Geneva last November and December could not reach a unanimous opinion regarding permanent criteria, that is, regarding a pattern of objective instrument readings that would give grounds for despatching on-site inspection teams, the Soviet Union proposed a month ago (GEN/DNT/PV.172, pages 6-7) that, during the initial stage of the control organization's work, inspection teams should be despatched on the basis of simplified criteria in regard to which the views of the Soviet and United States experts substantially coincided. This proposal of ours fully disposes of the objections raised by the United States and

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United Kingdom delegations on the subject of criteria, and opens the way to an agreement on a modus vivendi during the period when joint research is being carried out and agreement reached on the criteria concerning which there are divergences of opinion between the Soviet and the Western scientists.

In speaking about the series of important concessions made recently by the Soviet Union to the Western Powers at the Geneva Conference, we are bound to mention the Soviet Union's agreement to meet the views of the Western Powers also in regard to the time for starting the joint research programme.

We have fully complied with the United States request that joint research should begin immediately upon the signing of the treaty, without waiting for its ratification and entry into force.

This review of the state of our negotiations and of how matters stand with regard to the preparation of a treaty on the cessation of nuclear weapon tests shows that there are no real obstacles to the conclusion of a comprehensive treaty. We have already agreed on the vast majority of the articles of this treaty, and have worked out and in most cases agreed on the main provisions of a fairly extensive and workable system of control over observance of the treaty.

We have to begin with something. We should conclude a treaty, set up a control system and reach agreement on an annual quota of inspections. We should put the whole control system into operation and then verify its effectiveness in practice, and decide on measures for its improvement and for increasing its efficiency by applying the results of joint research.

It is towards this — the conlusion of a treaty providing for the prohibition of all nuclear weapon tests — that our efforts should be directed. But a new difficulty has cropped up on this path. The United States has created a fresh obstacle. The United States representative at this Conference, in proposing at our one hundred and seventy-ninth meeting on 29 February the conclusion of a treaty which would establish a threshold of magnitude 4.75 for underground events, stated the following:

> "This is a very concrete and specific offer. I do not see how this Conference can make significant strides forward until the Soviet representative either accepts it or makes equally specific offers in a similar context". (GEN/DNT/PV.179, page 5)

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Further he stated:

"...I urge my Soviet colleague to ... do his best to obtain from his Government a comprehensive and objective study of the United States proposal ... We are still ready ... to consider most carefully any constructive ideas the Soviet delegation may have with regard to it", (Ibid., page 6) that is, with regard to the United States proposal of 11 February.

Further, at the one hundred and eighty-fourth meeting on 10 March the United States representative stated that the United States side awaited the Soviet representative's reply to the United States proposal of 11 February.

From the United States representative's statement which I have quoted it follows that the United States intends to obstruct the progress of our negotiations until the proposal concerning the so-called threshold with regard to seismic events is adopted.

The Soviet Union's point of view on this matter is well known. Our scientists do not agree with the opinion of some United States and United Kingdom experts that there exists some sort of a threshold in the matter of detection and identification of underground nuclear explosions. In this respect we entirely hold the position formulated in the report of the 1958 Geneva Conference of Experts. Since, however, the United States and the United Kingdom have turned the question of the so-called threshold into a serious impediment holding back the progress of our Conference, in order to remove this new barrier to negotiations the Soviet Union Government has instructed me to submit for the consideration of the Conference the following proposal, which opens the door wide to a rapid settlement of all questions not yet decided at our Conference.

The Soviet Government, having examined the situation which has come about at the Geneva Conference, and desiring to overcome the obstacles which still impede the conclusion of an agreement, expresses its willingness to reach agreement on the basis of the following.

To conclude a treaty on the cessation of all nuclear weapon tests in the atmosphere, in the oceans and in outer space, and of all underground tests which produce seismic oscillations of magnitude 4.75 conventional units or above.

In regard to unidentified underground events producing seismic oscillations below magnitude 4.75 conventional units, which according to the United States contention do not lend themselves to control, the Soviet Government is prepared

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to agree to the United States proposal to institute a programme of joint research and experiments by the Soviet Union, the United States and the United Kingdom, on the understanding that all parties to the treaty assume at the same time the obligation not to carry out during that period any nuclear weapon tests producing seismic oscillations of magnitude 4.75 conventional units or below.

The Soviet Government hopes that this new step towards meeting the Western Powers will make it possible to conclude without delay a treaty on the cessation of nuclear weapon tests and, in the very near future, on the basis of experience of the operation of the control organization and the carrying out of joint research and experiments, to achieve the banning of all nuclear weapon tests for all time.

In introducing this proposal the Soviet Government is showing its goodwill, its sincere desire to overcome the difficulties and remove the obstacles which have arisen in the path of negotiations, in order to reach agreement in the very near future on the cessation of all nuclear weapon tests.

The Soviet delegation trusts that this proposal will be given favourable consideration by the United States and United Kingdom Governments, and that we shall receive from them a prompt and positive reply.

Mr. WADSWORTH (United States of America): Certainly we have heard an important statement today. For my part I am sorry that the proposal made by the Soviet representative was preceded by a thirty-five-minute harangue accusing the United States and certain elements in the United States of all kinds of plots and plans. Rather than answering these tendentious remarks by equally tendentious remarks, I shall content myself with denying anything that my Soviet colleague has said which appears to attack the motives of the United States Government. I would, of course, reserve my right at a later meeting to deal with some of these charges, after having studied the verbatim record. I do feel that Mr. Tsarapkin was extremely careful to avoid any mis-statements of actual facts: it was his interpretation of the facts that, I believe, should be contested.

As I know the Soviet representative would expect me to do, I shall reserve any statement on the proposal which he has made until after my Government has had an opportunity of studying it. I merely wish to say that it is an important statement and I believe it has been made in a serious attempt to see our Conference make some progress.

The CHAIRMAN (United Kingdom): I should like to speak for one moment as the United Kingdom representative.

I agree with my United States colleague that we have heard a very important statement this morning which we shall naturally study with very great care. However, there was just one point in it on which I myself should like clarification. Did the Soviet representative say that the Soviet Union would be prepared to embark on a joint research programme now, or was the proposal that the research programme would start after the signing of the treaty? If we could be clear on that I think it would help us to understand the exact proposal which has been put before us.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): We have already had an exchange of views earlier on this question. In replying to our view that joint research should be carried out after the treaty's entry into force and so forth, the United States representative urged that joint research should begin earlier because the procedure of formalizing the treaty, its ratification and so forth, might take a fairly long time owing to the constitutional requirements of some countries. For these reasons the United States representative proposed, and asked us to agree, to have that research started without delay as soon as the treaty was signed.

Having considered this proposal of the United States, we accepted it and agreed. In doing so we made an important concession and met the point of view of the United States and the United Kingdom. We agreed that joint research should be initiated without delay as soon as the treaty was signed.

Mr. WADSWORTH (United States of America): That leads me to put one other question. Are we to understand that this joint research is to take place over an indefinite period, or does the Soviet representative have in mind some time limit?

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): It will obviously be necessary to agree on a period for the research programme. This cannot of course last for an indefinite time. Evidently, when we take up practical discussion of the sections of the treaty which will deal with the research programme, we shall discuss the time question and fix a term for the execution of this joint research programme.

Mr. WADSWORTH (United States of America): I have just one further question which I think will help my Government to study this proposal. Is it the Soviet representative's idea that this agreement to refrain from testing below the limit of seismic magnitude 4.75 should be contained in the treaty, or would it be merely a unilateral act in the nature of a moratorium?

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): This should be reflected -- in one way or another -- in the treaty, and should form some part of the treaty. We consider that this is a very important part of the agreement, and this is the essential point of our proposal. We consider that this agreement should be part of the treaty. I do not want to predetermine its form. Whether it will be in the form of an article, or whether it will be contained in an annex, or perhaps it will be a separate protocol -- that we can decide later. I do not think it should be very difficult to agree on the form. But it should be part of the treaty.

The CHAIRMAN (United Kingdom): If there are no further speakers, we shall turn to the communique.

After an exchange of views the Conference decided to issue the following communique:

"The one hundred and eighty-eighth meeting of the Conference on the Discontinuance of Nuclear Weapon Tests was held at the Palais des Nations in Geneva on 19 March 1960 under the chairmanship of the representative of the United Kingdom.

"The Soviet delegation submitted a proposal to conclude a treaty on the cessation of all nuclear weapon tests including all underground tests producing seismic events of magnitude 4.75 or greater embodied in the United States proposal of 11 February.

"The Soviet Union accepted as well the United States proposal on carrying out a programme of joint research and experiments by the USSR, the United States and the United Kingdom, provided that all parties to the treaty simultaneously undertake not to conduct during this period any nuclear weapon tests producing seismic events of magnitude 4.75 or under.

"The next meeting of the Conference will be held on Monday, 21 March 1960, at 3 p.m."

The meeting rose at 10.50 a.m.

(Sir Michael Wright, United Kingdom)

It is in this light that my Government would now wish to study the Soviet proposal as such. As our Soviet colleague is aware, the United Kingdom has hitherto reserved its position with regard to the arrangements which might apply to underground tests below the threshold level, and this is a question to which we shall now wish to give most serious consideration. Other points will also need studying. This process of reviewing the Soviet proposal and its implications may take a little time, and I have no doubt that the Soviet representative will understand this, just as we have always shown understanding of his position in similar circumstances.

To conclude, I should just like to sum up one part of what I have said to make sure that I am not misinterpreting the views of the Soviet representative, and no doubt he will correct me if I am. The point I wish to touch on again is that I understand from what he has said today and at our last meeting that he is willing to talk over with us and to negotiate upon the various problems, questions and points which arise out of his proposals and which remain to be settled between us. I understand that the Soviet representative is willing, and indeed anxious, to talk them over with us and to negotiate upon them at this table in the same spirit as that in which my delegation will wish to negotiate with him. I just want to be quite clear that I have not misunderstood the position of the Soviet representative and, if I have, I am sure he will correct me.

The CHAIRMAN (United States of America): I should like to say, as representative of the United States, that I appreciate the prompt answers to those of our questions which our Soviet colleague has been able to answer today. I shall study his answers in the verbatim record and, of course, I hope that after reading the verbatim record he will be able to cover the few points he did not cover in his reply to my intervention today.

Speaking as Chairman, if no one else wishes to discuss anything else we shall turn to the communique.

The Conference decided to issue the following communique:

"The one hundred and eighty-ninth meeting of the Conference on the Discontinuance of Nuclear Weapon Tests was held at the Palais des Nations in Geneva on 21 March 1960 under the chairmanship of the representative of the United States.

"Discussion continued on the Soviet proposal of 19 March 1960.

"The next meeting of the Conference will be held on Tuesday, 22 March 1960, at 3 p.m."

The meeting rose at 4.5 p.m.

CONFERENCE ON THE DISCONTINUANCE OF NUCLEAR WEAPON TESTS

Official Records

Monday, 21 March 1960,
at 3 p.m.

Palais des Nations, Geneva.

VERBATIM RECORD OF THE ONE HUNDRED AND EIGHTY-NINTH PLENARY MEETING

Chairman: Mr. WADSWORTH (United States of America)

LIST OF MEMBERS OF DELEGATIONS PRESENT AT THE TABLE

United States of America:	Mr. J.J. WADSWORTH
	Mr. D. POPPER
	Dr. C. WALSKE
	Mr. D. MARK
	Mr. D. MORRIS
United Kingdom:	Sir Michael WRIGHT
	Mr. H.T. MORGAN
	Dr. F. PANTON
Union of Soviet Socialist Republics:	Mr. S.K. TSARAPKIN
	Mr. A.I. USTYUMENKO
	Mr. I.G. USACHEV
	Mr. O.A. GRINEVSKY
Representative of the Secretary-General:	Mr. T.G. NARAYANAN

The CHAIRMAN (United States of America): The one hundred and eighty-ninth meeting is open. Does any representative wish to speak?

If not, I should like to make some remarks in my capacity as the representative of the United States. When, at our last meeting, the Soviet representative made a statement containing his latest proposal regarding some sort of a moratorium on on testing below a threshold, I acknowledged immediately, of course, that it was an important declaration. As such, I said, it would have to be reviewed carefully by my Government before any official reaction from the United States could be given. This thought was echoed by a spokesman for the Department of State yesterday, when he indicated that the Department believed this to be an important and serious document meriting minute consideration and study. This is now being given and, though my colleagues -- especially the Soviet representative -- would no doubt like an immediate answer, I am sure that they will realize that this will not be possible; we hope, of course, that it will come as soon as possible.

In the meantime, I should like, as a means of facilitating my Government's study, to put several questions to my Soviet colleague concerning the details of his latest offer. There are other questions of subsidiary value, other areas -- largely administrative -- of comparatively unimportant political significance, which still need clearing up. There are also certain preliminary comments which should be made today on the merits of the Soviet idea.

As I indicated on Saturday, however, I do wish to take exception to portions of Mr. Tsarapkin's version of recent history and current events, in so far as these relate to our negotiations. We both agree, of course, on certain objective facts -- which are easy to agree upon -- such as the number of adopted treaty articles and the list of the chief problems remaining before us. It is at the next step that our paths diverge -- that is, as I said on Saturday, in regard to our interpretation of the situation in which we find ourselves and the reasons therefor. For the United States delegation the technical difficulties which have unexpectedly arisen since 1958 are evident and predominant. In our view, these stand in the way of achieving an effective control system at the outset. For the Soviet representative, apparently there are plots, conspiracies and intrigues.

I have, unfortunately, not kept count of the number of times that Mr. Tsarapkin has deemed it necessary to attack in this Conference the motives either of my Government or of leading persons in United States life. These interpretations,

(The Chairman, United States)

amounting to accusations, have never advanced our work in the slightest. Undoubtedly they never will because, essentially, they are mere polemics, and not very accurate polemics at that. They cannot change the course of events in the United States, nor could they ever do so, as they are based on what is apparently a misconception of the way in which we operate. The Soviet representative's current preoccupation is that the opponents of this treaty in the United States have manufactured technical pretexts for rejecting a comprehensive treaty, with the aim of making possible a resumption of nuclear weapon tests. Furthermore, he alleged that the views of these individuals have prevailed in the United States Government itself, and that they are bending it to their will.

The facts are that the United States, represented by the President, has been in favour of an all-out test ban since the beginning of this Conference; but it has always insisted -- from the very first day, 31 October 1958 -- that it could accept such a ban only if adequate controls over its effectuation could be forged, agreed upon and implemented. It is the latter condition which United States scientists regret cannot now be fully satisfied, as an impartial review of the records of Technical Working Group 2 will confirm. This does not change our feeling that a comprehensive and effective test prohibition would be a most desirable thing, which ought to be put into effect at once if feasible; but it does make us realize that other factors must be taken into account in determining feasibility.

I have put these factors into our verbatim records many times. Briefly, they are that inadequately controlled treaty obligations could give rise to all sorts of new suspicions and tensions among nations, could establish a bad and dangerous precedent in other disarmament fields, and could lead to an upset of the world military power balance.

It was these weighty considerations, and nothing else, which led to the United States threshold proposal of 11 February. We were guided by the sound principle of banning only what could be controlled and of extending the ban as rapidly as a stepped-up research programme for control system improvements would allow. The offer to arrange for a joint research programme and to lower the threshold as soon as justifiable would scarcely have been made by a nation guided mainly by a desire to resume nuclear tests. Indeed, the President, who alone makes major decisions in these matters, has made it clear that no decision to resume testing has been made.

(The Chairman, United States)

I hope that my remarks today will give my colleagues a better perspective of the serious and vital problems which will confront the United States in its efforts to reach a decision on the latest Soviet proposal. I am sure, however, that my Government will appreciate clarification from the Soviet representative of certain phases of his Government's plan. I shall put all of these comments and questions into the record at once rather than ask my Soviet colleague to listen to one question and then to answer it immediately, which I do not believe would be a fair or an orderly way of proceeding. In the way I propose Mr. Tsarapkin will have an opportunity to study the exact wording of the question and to give whatever thought is necessary rather than answering immediately.

Our questions are divided into several categories. Some of them are based on assumptions; others are based on what has been said in the past; still others are on my list because we have had insufficient discussion of certain of these matters to have become familiar with the Soviet position on them.

The first category of questions concerns the joint research programme, its period, the result of either its success or its failure, and so forth. The first question has to do with the duration of the agreement to refrain from testing — which, as we understand it, was originally a concurrent idea of the Soviet Union. I realize that I asked this question on Saturday and the answer was that it was a matter for negotiation; yet my Government still would like to get some idea as to how long the Soviet scientific community feels that it would be necessary to carry out this programme. Are we to assume that these periods are not necessarily concurrent? Secondly, what would happen at the end of the period? If, in the opinion of the scientists, the controls were still not completely effective, would the obligation not to test nevertheless persist? Would there be provision for some sort of review? What is the Soviet belief in this particular question? Thirdly, what is the scope of the proposed research programme? This is a matter which we have discussed only briefly in the past in connexion with research programmes. In some cases it has seemed that the Soviet delegation has declared that the programme should be limited to criteria; in other cases it seems to have been admitted that in a study of the question of criteria it would be necessary to cover all aspects of the capabilities of underground detection and identification. So we should like to know how Mr. Tsarapkin views this particular aspect.

(The Chairman, United States)

The second series of questions concerns the level of on-site inspections and the threshold of magnitude — the latter has now provisionally been accepted by the Soviet Union. The first question has to do with the magnitude scale. I can recollect that after 11 February, when we put forward our threshold plan, Mr. Tsarapkin complained that Western and Soviet scientists were not in agreement as to the magnitude scale. That was one of the reasons why it was impossible to equate magnitude scale with kiloton yield. I would remind my colleagues that our proposal was that we adopt the unified magnitude scale, which could provide the most non-controversial basis for applying the threshold concept. My question is: does the Soviet delegation feel that this scale can be adopted?

Next, the Soviet proposal presented on Saturday did not specifically mention the threshold programme put forward by the United States, but in the communique following the meeting there was mention of such a programme. The text of the communique could have meant that the magnitude level of 4.75 was the only thing embodied in the United States proposal. In clarification of this, we should like to know whether the Soviet Union can accept all of the United States proposal having to do with the 4.75 threshold and whether or not the level of on-site inspections which we proposed for that particular plan now enjoys its confidence. If, as I rather suspect, the answer to that is "No", we should still like to know what the Soviet proposal would be regarding a quota connected to this new plan. This new plan being somewhat a combination of thoughts, it occurs to my delegation that we are asked to place a permanent ban upon explosions above magnitude 4.75, and naturally we would expect that full control would go with that.

We are asked to refrain, at least temporarily, from explosions below magnitude 4.75. Now the question is: do we have a quota above the threshold, or do we have a quota below the threshold, or do we attempt to negotiate a quota for the entire range? I am sure that my Soviet colleague will see the significance of this question. On the one hand, we feel that we do and can have adequate control above the threshold, and naturally our thoughts and beliefs about a quota of on-site inspections above the threshold can be more surely and confidently argued. On the other hand, we are asked to refrain from exploding devices below the threshold, and we have had no clarification as to the type of control, and therefore the type and size of quota, that our Soviet colleague would like to see for the lower ranges.

(The Chairman, United States)

On the same lines and going back to the question of criteria, it will be remembered that the Soviet counter-proposal to the United States proposal of 11 February was that certain simplified criteria embodying some of the United States recommendations, but not all of them, might be adopted — and for the entire range of matters covered in a comprehensive treaty. Our question is whether or not the Soviet Union would be prepared to accept the United States suggestions for altering, amending, and, as we think, improving the simplified criteria.

The last area of questions that we feel need some clarification is that of high-altitude explosions. The wording of the Soviet proposal seems to indicate that high-altitude controls would be complete, that a ban on all high-altitude and, indeed, cosmic-space explosions would be complete. The USSR representative surely recollects that this is not the suggestion as worded by the United States, although the United States cannot at this time say that a complete ban is impossible. We had some colloquy which indicated that none of us was exactly sure which of the various techniques suggested by the Technical Working Group on high-altitude explosions could be put into effect immediately, which should be put into effect later, and which might be put into effect ultimately. We would therefore like to know whether our Soviet colleague can tell us just what kind of control system is proposed for installation in the high-altitude environment, what elements it would contain and at what intervals such elements of the high-altitude system would be installed. We understand, of course, that any answer to a number of these points would not be the final word on this most complicated technical matter, and the United States delegation has already frankly admitted several times its lack of complete knowledge on this subject. However, it would be helpful to my Government to know what is considered to be not only necessary but feasible, both technically and economically, in this area.

Another question in this area is as follows: what would be done about high-altitude or cosmic-space tests which could not be identified by the initially installed system? In the event that the three Governments concerned and their technical advisers feel that at first we must walk instead of run in this high-altitude area, there will be definite gaps in the capability of the system, gaps which have already been pointed out by the high-altitude technical working group, and we should like to know what would be done about those gaps.

(The Chairman, United States)

Our final question is one which of course is not covered in any draft proposal which has been placed before us but which, I believe, would be of some value in bringing about an understanding of the Soviet attitude to which I refer. As regards the underground environment, in the event that effective control of small underground explosions proved impossible and if the proposed temporary prohibition against such explosions lapsed, would the remainder of the treaty continue in effect?

These are the questions which, on this first brief review of the thoughts contained in the Soviet proposal, we have felt it necessary to advance in order to help my Government evaluate the proposal which has been made. I think that a reading of them will reveal the fact that we are not attempting to put any barriers in the way; we merely wish to find out what the sponsor of this proposal feels about the various matters, largely mechanical and somewhat technical, which will of course come to light when and if we can begin a detailed negotiation of the matter — and particularly when we can begin a detailed elaboration of the provisions of annex I.

That completes my remarks as representative of the United States.

Mr. TSARAPKIN (Union of Soviet Socialist Republics) (translated from Russian): At the last meeting, held on 19 March, the Soviet delegation submitted on instructions from the Soviet Government a most important proposal, which enables us to conclude our negotiations here speedily and successfully. In submitting this proposal the Soviet delegation reviewed in detail the course of the negotiations and the situation which had arisen in them.

We believe that the true significance of any proposal and the part it may play can be correctly appraised only if it is examined against the general background of our Conference and in the light of the situation which has developed in the Conference. That analysis was necessary. I realize that my United States colleague may not like certain unpleasant truths concerning the situation which has developed in the Conference. All I can say is that all the facts set forth by me at the last meeting are correct and in keeping with reality, and I am happy to note that this was acknowledged by Mr. Wadsworth himself.

Such excursions into the past, or attempts to analyse the course of our negotiations, have been made more than once, not only by the Soviet delegation but also by the representatives of the United States and the United Kingdom. In

(Mr. Tsarapkin, USSR)

this connexion I should like to recall a similar intervention made by the representative of the United States on 11 February, when he introduced his proposal concerning a treaty with a so-called threshold. I venture to quote Mr. Wadsworth's own words:

"I have reviewed these developments not in order to engage in polemics about the past ...". (ENDC/PV.170, page 4)

I should like to apply that very same remark to my review of our negotiations at the meeting of 19 March. In making that review it was not my purpose by any means to engage our Conference in, or to divert it into, polemics about the past. If that had been our purpose, there would have been no need to introduce our new proposal, which represents an extreme step towards meeting the position of the Western Powers. I think that the representatives of the United States and the United Kingdom will do well to concentrate their attention and goodwill on the proposal we have introduced, and not on fresh polemics concerning how and by whom the state of our negotiations is to be analysed and appraised. On that you have one point of view and we another. The most important matter upon which we must concentrate is the proposals which we put forward on 19 March and which enable us to conclude our negotiations promptly and successfully.

At our last meeting the representatives of the United States and the United Kingdom asked us certain questions. Today those questions have considerably expanded. Their number at any rate has considerably increased, although they repeat much of what has been asked before and to which, it appears to us, we have given our answers. In particular there is the question of the timing and duration of the joint research and experiments. In regard to the time of initiation of this research programme, we think that we might even now record our common agreement to work on the joint research programme — its drafting and performance — immediately after the signature of the treaty, without waiting for the treaty's ratification and entry into force. I gave a definite reply to a similar question put by Mr. Ormsby-Gore at our last meeting. This aspect of the question, therefore, should now be completely clear to the United States and the United Kingdom representatives. On this point we have gone all the way to meet you. We have accepted your proposal and granted your request, and so we could today record the complete agreement of the Conference upon this matter.

(Mr. Tsarapkin, USSR)

One more question arises in this connexion which Mr. Wadsworth asked today in a more or less elaborate form, namely, who will draft this programme? Will it coincide with the period of the moratorium? What will happen if this joint research programme does not lead to a successful completion of the assigned task? To that question I might reply as follows.

We consider that the drafting of the joint programme should and can be entrusted to the preparatory commission. There is an appropriate clause in the annex we have agreed on regarding the preparatory commission according to which the commission, which is to commence work before the entry into force of the treaty itself, will have to draft the joint programme. On the staff of the preparatory commission, as you know, there will be specialists from all our countries. It can carry out the drafting of this programme rapidly and at the appropriate level.

Will this programme coincide with the period of the moratorium? I think two aspects are here involved. We assume that research will be one branch of the activities of the control organization which will be permanent in character. The control organization — we have already adopted a provision, articles, to this effect — will engage at all times in research activities, will work to improve the methods of detection and identification that have already been adopted and are in operation, and will carry out research to improve the apparatus, instruments and equipment the control system has at its disposal. Thus the research work of this plan is not linked by any definite, limited period. It is another matter when we come to the joint research programme connected with the United States proposal for a ceiling. This programme, which will provide for research directed towards clarifying and increasing the efficiency of methods of detecting and identifying seismic events below the magnitude threshold specified by the United States, will obviously have some kind of time-limit. We feel that five years or four years, for example, would be roughly the suitable length for this programme.

Thus, the question of a moratorium and the question of this research programme are closely interrelated.

What will happen if work in this research programme is not completed successfully? I do not know what will happen. This is a purely hypothetical question. We consider that, if for any reason it so happened that your specialists and our specialists, working together within the control organization or control system — we do not admit the possibility, but if we took as pessimistic a view of the matter as you do — failed after four or five years to work out together improved methods

(Mr. Tsarapkin, USSR)

of detecting and identifying seismic events below the United States figure of threshold magnitude, that fact should not automatically release the parties to the treaty from their obligations regarding the moratorium and should not mean that the treaty would terminate or be liquidated. No. If such a situation even did arise -- and we consider it highly unlikely -- then the Governments concerned would have to discuss the situation created and agree on further measures in connexion with it.

That is our reply to the questions of the first category that you have addressed to us.

As regards the other categories of question, such, for instance, as the question of the level of the inspection quota, I can tell you here and now that we firmly adhere to our position that the question of the inspection quota must be solved as a political one. Your attempt, in accordance with your previous position, to link it somehow to the number of unidentified seismic events is therefore unacceptable. We cannot agree with that approach. You already know our position. In this respect it is absolutely firm, and we cannot agree about the inspection quota on any other basis. We consider that this should be a political decision, a political compromise, and that you have more than sufficient grounds for moving towards the Soviet standpoint in this matter and agreeing. We regret that almost a year has passed and we still cannot agree with you on this matter.

Regarding the different evaluations of magnitude to which I have referred, we propose — at least, we shall assume — that no threshold should be fixed with regard to inspection. We consider that events both above and below the so-called threshold of magnitude will be subject to inspections within the limits of the agreed quota. Thus questions concerning the disputes which different approaches to the determination of magnitude may produce are eliminated and have no meaning whatever.

Let me now turn to high-altitude explosions. Your position on high-altitude explosions is not entirely clear to us. We shall still try to read and study your position carefully in the verbatim record. We know that the proposals you submitted on 11 February contain a rather vaguely worded passage on high-altitude explosions which permits, or at any rate admits, the idea that you intend to leave some sort of a loophole enabling explosions to be carried out at high altitudes. Later you explained to us that this is not so, and that it is not in your mind that nuclear explosions at high altitudes must take place; you merely consider that, in the matter of control over nuclear explosions at high altitudes and in

(Mr. Tsarapkin, USSR)

outer space, for technical and economic reasons not everything can be put into operation just yet and that perhaps a certain time may pass before such possibilities will appear. If this circumstance led you to phrase your proposal about control over nuclear explosions at high altitudes in such vague terms, then we would ask you to put it more clearly and definitely.

We at any rate believe that — whether the control of nuclear explosions at high altitudes and in outer space will be effected by operating immediately all the methods set forth in the experts' recommendations last summer, or whether the United States assumes that such control will take effect — perhaps not immediately to a full extent but in certain stages — the provision about the prohibition on carrying out nuclear explosions at high altitudes should be written into the treaty by us without reservation.

These are the preliminary answers to your questions which we can give now. I should like to make a few more remarks, so that no questions may occur to you in the future.

With regard to the research programme and experiments, we have already told you that we accept the proposal to carry them out. We believe that the experiments to be conducted in the course of this research programme should be made with conventional chemical detonations, not nuclear weapons; because for study of the underground effects in order to increase the efficiency of the instruments and apparatus which record them we believe that it is quite sufficient to use chemical explosives.

I have already told you that we think it advisable and essential that on-site inspection within the quota limits be carried out both above and below the so-called threshold of magnitude. We think this is a perfectly reasonable provision and would simplify our task considerably.

I should like to remind you once again, in order to prevent further questions from arising, that we have already told you that it will be possible to review the inspection quota in the light of practical experience of the control system's working. The Soviet Government believes that the inspection quota should be reviewed by the same procedure as is laid down in the article adopted by us on the periodic review of the system: namely, that the first review should take place two years after the entry into force of the treaty, and subsequent reviews annually.

Those are the comments we wished to make on the questions put by you to-day and at the previous meeting.

Sir Michael WRIGHT (United Kingdom): I have listened with interest to the interventions of my colleagues today, and not least to the queries which the United States representative put to our Soviet colleague and to Mr. Tsarapkin's comments upon them.

I do not myself propose to add today any specific questions on behalf of my delegation. All the points which have been raised — and perhaps, indeed, other points which have not been touched upon today — will have to be settled in due course. Some of them will obviously take longer to settle than others. It is as well that all delegations should be thinking about them even if detailed statements of position are not immediately, or in all cases, forthcoming. My own delegation will certainly need some time to reflect on these matters.

Today I propose to confine myself to a few remarks of a more general nature with respect to the proposal made by the Soviet representative at our last meeting. As Mr. Ormsby-Gore said at the time, we regard this as an important proposal, an important development for our Conference as a whole, which the United Kingdom Government will want to study with very great care. I want to assure the Soviet representative today that my delegation and my Government will be studying the proposal in a spirit which corresponds, we believe, with the intentions of the Soviet representative and of the Soviet Government in making the proposal. We see this proposal as a declaration of principle rather than as a fully formulated and detailed proposal for actual treaty provisions.

It appears to us that the essence of the Soviet proposal consists in the acceptance by the Soviet Union of the principle that in the initial phase of a comprehensive treaty it will be necessary to apply different treatment to underground tests above the threshold from the treatment applied to such tests below the threshold. In essence, the Soviet representative has now, as we understand it, accepted this proposition which both Western delegations have been urging upon him for reasons amply explained, and in accepting it he has made the condition that no testing of any kind by the parties shall be permitted in the initial phase. At the same time, of course, the Soviet representative has also accepted the specific threshold level proposed by the United States, as well as the United States proposal for joint research aimed at improvement of underground controls and at the consequent lowering and eventual elimination of the threshold. It appears to us, I repeat, that the Soviet delegation has been concerned primarily to put forward these determining principles or characteristics of the solution which the Soviet Government is prepared to accept.

(Sir Michael Wright, United Kingdom)

From the comments of our Soviet colleague today, as well as from his statements at our last meeting, it appears to me that he is suggesting that if these principles are found mutually acceptable the actual treaty provisions and the details will be matters for discussion or negotiation between us. If I am wrong in this understanding of the Soviet representative's approach, no doubt he will correct me; but that is how I understand his position.

As I say, my Government will certainly be prepared to examine the Soviet proposal in this light. We shall be prepared to examine it as a proposal of principles aimed at enabling the Conference to circumvent the technical disagreements which still exist and to reach a practical solution which takes account of those disagreements. In this sense the Soviet proposal seems to us quite in accord with the spirit in which we have been trying to negotiate a way out of our difficulties since January of this year.

I remember our United States colleague at our first meeting after the recess, on 12 January, urging that our political Conference should not:

> " ... ignore the very real technical obstacles to a comprehensive treaty, but rather that our meetings should focus on methods whereby politically devised procedures and formulas could overcome existing technical problems, without disregarding them." (GEN/DNT/PV.151, page 9)

I myself have taken the same line, and it is with satisfaction that we have noted the attempts of the Soviet delegation to deal with matters in this spirit.

The Soviet representative drew our attention at the last meeting to the recent concessions made by his Government in agreeing to the temporary use of simplified criteria and in accepting a programme of joint research to begin immediately upon signature of a treaty, without waiting for its ratification. He spoke of that again today.

The Soviet Government has now accepted the principle of a phased approach with a distinction initially between tests above and below the underground threshold and with a programme of research covering, if I understand rightly, the whole question of underground controls. These successive advances in the Soviet position have seemed to us important steps forward in the right direction, and we welcome them as such. Other questions, of course, remain, but it does seem to us that our negotiations are now on a more hopeful path.

APPENDIX 3

CONFERENCE ON THE DISCONTINUANCE
OF NUCLEAR WEAPON TESTS

REPORT OF THE TECHNICAL WORKING GROUP I ON THE DETECTION AND IDENTIFICATION OF HIGH-ALTITUDE NUCLEAR EXPLOSIONS

At the direction of the Conference on the Discontinuance of Nuclear Weapon Tests, the Technical Working Group has examined the possible techniques for the detection and identification of high-altitude nuclear explosions under the following terms of reference:

"The Technical Working Group should assess the capabilities and limitations of possible techniques for the detection and identification of nuclear explosions at high altitudes (more than 30-50 kilometres) above the earth and, on the basis of the discussions and conclusions of the Geneva Conference of Experts, recommend techniques and instrumentation for consideration by the Conference for incorporation in the Detection and Identification System".

The Technical Working Group considered the detection of nuclear explosions in the region extending from 30-50 kilometres above the earth to hundreds of millions of kilometres from the earth.

Recognising that the Geneva Conference of Experts in 1958 considered that it is possible to use the methods of recording gamma radiations and neutrons by instrumented earth satellites, pointing out the capabilities and limitations of the methods of recording gamma radiations, and also the methods of recording optical phenomena and ionospheric phenomena at ground stations for the detection of nuclear explosions at high altitudes, the Technical Working Group additionally considered and assessed the capabilities and limitations of these techniques. The Technical Working Group has also assessed the capabilities and limitations of new techniques of detection based on observing electrons trapped in the earth's magnetic field by instrumented earth satellites, soft thermal X-rays by instrumented earth and solar satellites, and backscatter radar signals from the ionosphere at ground stations.

As a result of further consideration of the detection and identification techniques mentioned in the conclusions of the Geneva Conference of Experts and of methods and techniques which are not mentioned in the conclusions of the Experts, the Technical Working Group has arrived at the following conclusions in regard to the capabilities and limitations of the possible techniques for the detection and identification of nuclear explosions at high altitude (more than 30-50 kilometres) above the earth.

A. Detection of High-Altitude Nuclear Explosions by means of Apparatus installed in Satellites

1. It is technically feasible by means of a multiple coincidenced arrangement of suitable counters, for example scintillation counters, to detect the prompt gamma rays from a one-kiloton nuclear explosion at an estimated distance of about 300,000 kilometres when the explosion is unshielded; the distance could be reduced by one order of magnitude when the explosion is shielded in a manner that would increase the total weight of the device by several times. The number of counters necessary for recording would be lower if the satellites were located outside the inner radiation belt of the earth and greater if the satellites were located within the inner radiation belt. The counters must be separated by a sufficient distance to avoid signals due to cosmic ray showers.

2. It is technically feasible by means of suitable counters, for example scintillation counters, with appropriate geometry and capable of discriminating against the hard component of penetrating particles, to detect the delayed fission gamma rays from a one-kiloton nuclear explosion at an estimated distance of about 300,000 kilometres. When operated outside the inner radiation belt of the earth the system of counters would be simplified. This method is not sensitive to shielding of the nuclear explosion.

3. It is technically feasible by means of neutron counters, employing a moderator and not located within the inner radiation belt of the earth, to detect the prompt neutrons from a one-kiloton nuclear explosion at an estimated distance of up to 100,000 kilometres when unshielded and at shorter distances when shielded. The weight of shielding would be smaller than in the case of gamma radiation for a comparable reduction in detection distance. At distances of the order of 10,000 kilometres, it is possible to detect such an explosion by means of delayed neutrons. This method of detecting delayed neutrons is not sensitive to shielding of the nuclear explosion.

4. It is technically feasible by means of an array of photomultipliers or a system of appropriate counters (for example, thin inorganic scintillation counters covered with thin foils) to detect soft thermal X-rays from an unshielded 10 kiloton nuclear explosion at an estimated distance of a few hundred million kilometres when the detector is not located within the earth's radiation belt. When the X-ray detector is located within the earth's radiation belt, the estimated detection distance is reduced by an order of magnitude. When the explosion is shielded

by means of a reflector having large dimensions and a weight which is comparable to the weight of the device, the estimated detection distances of high yield nuclear explosions (in the megaton range) can be reduced by one or two orders of magnitude and by an even greater amount for low yield nuclear explosions (in the kiloton range). Lighter shields will accomplish the same reduction in detection capability against detectors covered by foils.

5. It is technically feasible by means of simple electron counters to detect the electrons trapped in the earth's magnetic field and resulting from a one-kiloton nuclear explosion occurring between approximately 70°N and 70°S magnetic latitude and at altitudes ranging from 100-700 kilometres, depending on the longitude, up to an altitude of 20,000 kilometres. Outside this special region the capabilities of this method decrease very rapidly.

6. A group of 5-6 earth satellites, maintained in appropriate orbits at altitudes of several tens of thousands of kilometres, allows for complete earth surveillance and, given the presence of instrumentation listed in paragraphs 1 - 4 of this section, is capable of detecting nuclear explosions at altitudes above the altitude at which radiation could escape from the atmosphere (i.e. 30 kilometres for gamma rays and neutrons and 75-100 kilometres for soft thermal X-rays) and also nuclear explosions in cosmic space up to distances in accordance with the recording capabilities of detectors of radiation listed in paragraphs 1 - 4 of this Section. If complete earth surveillance were carried out by satellites operating at lower altitude, a larger number of satellites would be required, depending on the altitude. Such detection systems cannot detect nuclear explosions which might be carried out behind the moon or the sun away from the earth

7. Since the difficulty of establishing a satellite in orbit around the earth increases with altitude and since the difficulty of establishing a system of satellites at a given altitude increases as the number of satellites becomes greater, the Technical Working Group notes that it is technically feasible to detect high altitude nuclear explosions by means of techniques specified in paragraphs 1 - 4 of this Section with various systems of earth satellites. It is possible to detect explosions over the entire surface of the earth by using satellites with lower orbits and correspondingly increasing the number of satellites. A system of satellites ensuring full surveillance of the earth will

At the same time ensure the surveillance of a considerable part of the earth by more than one satellite at a time. Such detection systems cannot detect nuclear explosions which might be carried out behind the moon or the sun away from the earth. If the use of satellites is to be limited to detecting explosions carried out above certain altitudes over the earth, the number of satellites may be correspondingly reduced. For example, while 50-70 satellites at 700 kilometres and 10-20 satellites at 2,000 kilometres are needed for complete earth surveillance, a system of 8-10 satellites will detect nuclear explosions except in limited predictable areas near the earth extending to altitudes of about 550-2,000 kilometres for the 700 kilometre orbits and to altitudes of about 120-750 kilometres for the 2,000 kilometre orbits.

The number of satellites required depends upon the accuracy of their position in the orbits.

8. A single satellite equipped with simple electron counters, and in an appropriate orbit which intercepts the region in which electrons may be trapped in the earth's magnetic field, could detect the trapped electrons from nuclear explosions occurring in the region indicated in paragraph 5 of this Section.

9. The systems of earth satellites described in paragraphs 6 and 7 above cannot detect nuclear explosions carried out in certain regions of controlled space, namely, behind the moon or the sun away from the earth. Unshielded nuclear explosions in these regions can, however, be detected by the apparatus for X-ray detection, assessed in paragraph 4 above, when installed in a system of four satellites circling the sun in appropriate orbits, provided data from these satellites is regularly received on the earth. Bearing in mind that shielded nuclear devices will have to be stabilized in all cases, the Technical Working Group notes that for nuclear explosions at great distances from the earth, heavier shields would be required to reduce the capabilities of such a system of solar satellites than would be required to reduce the detection capabilities of the earth satellite system.

B. Detection of High Altitude Nuclear Explosions by means of Apparatus installed at Control Posts

1. It is technically feasible by means of a system of optical detectors, mounted behind telescopic lenses, to detect the visible light from a one-kiloton nuclear explosion at estimated distances of about 100,000 kilometres during the day and about 300,000 kilometres during the night. These ranges will be three times greater for megaton explosions. The minimum altitude for complete surveillance is determined by both the control post spacing and the angular aperture of the detector. For the 1,700 kilometre spacing of control posts the minimum altitude for complete surveillance is about 1,000 kilometres for a 60° aperture and about 2,500 kilometres for a 30° aperture. Larger apertures would allow a reduction of the minimum altitude for complete surveillance depending on atmospheric conditions. The performance of this detection method is not substantially affected by shields. Cloud cover over a control post will nullify the effectiveness of the detector at that post. However, simultaneous cloud cover for all line-of-sight posts is unlikely for a nuclear explosion at very high altitude.

2. It is technically feasible by means of an optical detector and a narrow band filter, mounted behind a wide angle lens, to detect the visible fluorescence created in the upper atmosphere by thermal radiation from a 10-kiloton nuclear explosion at an estimated distance of several hundred thousand kilometres from the earth. Detection at somewhat larger distances is possible at night. For the 1,700 kilometre spacing of control posts, the minimum altitude for complete surveillance above the earth is about 400 kilometres. For heavy cloud cover the range detection is reduced by a factor of ten.

3. It is technically feasible, by means of a network of 25 to 50 backscatter radar installations operating at frequencies of 10-30 megacycles, to detect the appearance of additional ionization at the source of the explosion and of additional ionization in the atmosphere produced by high-altitude nuclear explosions with a yield above one kiloton at altitudes from 30-50 kilometres and extending to several thousand kilometres. The location of the explosion and the region of additional ionization might be separated by considerable distances. Additional ionization in the atmosphere at the two magnetic conjugate points of the earth arises from nuclear explosions occurring in regions of space limited by 70°N and 70°S magnetic latitudes and by altitudes from 70-100 kilometres up to several thousand

kilometres. Outside this region of latitudes increased ionisation could occur only at the magnetic conjugate point nearer the explosion. The main difficulty with this method is the occurrence of natural phenomena giving similar signals. The use of this method is substantially more difficult in polar regions where auroras occur. Simultaneous observations from several stations are desirable to help in discriminating nuclear explosions from the natural background. The use of this method might produce interference with instruments at control posts and would require measures to overcome this interference.

4. It is technically feasible by means of the observation of absorption of cosmic radio noise in the ionosphere to detect the changes in the ionosphere produced by unshielded nuclear explosions of 10-20 kilotons occurring in the height range from 30-50 kilometres up to an altitude from thousands to tens of thousands of kilometres, depending on the spectrum of thermal X-rays produced by the nuclear explosion and on the type of detection apparatus employed. The explosion and the disturbance of the ionosphere can occur at considerable distance from one another. The main difficulty with this method for identification purposes is the possibility of the occurrence of effects of a similar type in the sunlit ionosphere during so-called "sudden ionospheric disturbances", during auroral disturbances and during solar noise storms. Detection of the absorption produced by thermal radiation could be markedly reduced by shielding. For the 1,700 kilometres spacing of control posts the minimum altitude for complete surveillance of nuclear explosions of 10-20 kilotons is about 100 kilometres.

5. The electromagnetic pulse method for detection of nuclear explosions was recommended by the Geneva Conference of Experts for inclusion in the Detection and Identification System for the detection of atmospheric nuclear explosions. It is technically feasible to use this method for the detection of nuclear explosions taking place at altitudes up to about 1,000 kilometres and perhaps higher. The method suffers from possible confusion with lightning flashes in thunderstorm areas. This method has particular value in the polar areas of the aurora where lightning flashes are rare.

C. General Remarks on the Assessments

All assessments of the capabilities and limitations of the methods for the detection of nuclear explosions at high altitudes are based on the present level of scientific knowledge. The assessments of ranges of detection of high altitude explosions were made in the light of present knowledge regarding background levels due to natural phenomena. Since knowledge concerning the natural phenomena in the upper atmosphere and cosmic space is still incomplete but in a state of rapid growth, it is considered that the actual detection ranges attainable by the various methods discussed above will in the future be more precisely determined. The detection ranges of the methods assessed in Section A, paragraphs 1 - 4, have been estimated so that the number of signals, caused by known or estimated backgrounds from natural phenomena, which could be mistaken for a nuclear explosion shall be negligibly small. For the methods assessed in Section A paragraph 5 and Section B paragraphs 1 - 5, no assessment of the rate of erroneous signals is possible at present.

D. Recommendations on Techniques and Instrumentation for the Detection and Identification of Nuclear Explosions at High Altitudes above the Earth for Consideration by the Conference for Incorporation in the Detection and Identification System

The Technical Working Group, on the basis of the discussions and conclusions of the Geneva Conference of Experts, makes the following recommendations concerning techniques and instrumentation for consideration by the Conference for incorporation in the Detection and Identification System:

1. A system should be established consisting of 5-6 earth satellites placed in orbits at altitudes of more than 30,000 kilometres. The orbits should be so established and the relative positions of the satellites so arranged as to ensure complete surveillance of the earth and outer space in accordance with the capabilities and limitations of the techniques set forth in Section A, paragraphs 1-4 and 6, above. The following instruments should be placed in the satellites:

(i) a multiple coincidence arrangement of suitable counters for the detection of gamma rays, as assessed in Section A, paragraph 1;

(ii) suitable counters for detecting delayed gamma rays, as assessed in Section A, paragraph 2;

(iii) neutron counters, employing a moderator, as assessed in Section A, paragraph 3;

(iv) a photomultiplier array or thin inorganic scintillation counters covered with thin foil for detection of soft X-rays, as assessed in Section A, paragraph 4.

2. In the event that it is deemed necessary for technical or economic reasons to establish an earth satellite system at low altitudes, the following two systems are recommended for consideration:

(a) A system of 6-10 satellites appropriately placed in near-circular orbits at altitudes of 500-700 kilometres which would assure complete surveillance of the space around the earth except in limited and predictable regions below an altitude of about 2,000 kilometres.

(b) A system of 2-4 satellites appropriately placed in near-circular orbits at altitudes of 500-700 kilometres which would ensure complete surveillance of the space around the earth except in limited and predictable regions below an altitude of about 10,000 kilometres.

The instrumentation and equipment should be those set forth in paragraphs 1 and 5 of this Section. It is to be understood that the systems described in paragraphs 1, 2(a) and 2(b) of this Section shall not be operating simultaneously.

3. A satellite should be placed into an appropriate elliptical orbit around the earth to provide maximum coverage of the region in the earth's magnetic field in which electron trapping occurs, as assessed in paragraphs 5 and 8 of Section A. The satellite should have sufficient payload to carry a simple electron counter and suitable equipment to ensure that all the required data can be transmitted to a suitable number of control posts.

4. In the event that it is deemed necessary to extend the capabilities of the system to provide increased coverage of the regions behind the moon and the sun away from the earth and to make nuclear testing in space more difficult by increasing the weight of shielding necessary for concealment, a system of four satellites should be placed in appropriate solar orbits, of radius approximating that of the earth around the sun, when the state of technology permits. Each satellite should have sufficient payload to carry a photomultiplier array or thin inorganic scintillation counters covered with thin foil, for detection of soft X-rays as assessed in paragraph 4 of Section A and suitable transmitting equipment to ensure that all the required data can be transmitted to a suitable number of control posts.

5. Each satellite should carry instrumentation to achieve the maximum reliability and range of detection of nuclear explosions in space and carry apparatus for checking the performance of the equipment of the satellite. All required data, including levels of background, signals, and performance data should be transmitted to a suitable number of control posts. Suitable equipment for receiving and analyzing data should be installed in these control posts in order to ensure the rapid and reliable analysis of signals received from the satellite.

6. The following techniques and instrumentation should be installed at ground control posts:

a. Multiple channel optical detectors, suitable for observing direct visible light as assessed in Section B, paragraph 1, at each of the control posts.

b. Optical equipment suitable for observing fluorescence in the upper atmosphere as assessed in Section B, paragraph 2, at each of the control posts.

c. Equipment suitable for measuring the absorption of cosmic radio noise in the ionosphere operating at two or more frequencies in the 30-100 megacycle range, as assessed in Section B, paragraph 4, at each control post.

d. Equipment suitable for recording radio signals as already recommended for inclusion at control posts in the Report of the Geneva Conference of Experts.

* * *

For various reasons the Technical Working Group did not come to an accord regarding a recommendation concerning the matter of detection of nuclear explosions at high altitude by the method of backscatter radar as described in Section B, paragraph 3.

APPENDIX 4

CONFERENCE ON THE DISCONTINUANCE
OF NUCLEAR WEAPON TESTS

TECHNICAL WORKING GROUP 2

Letter dated 18 December addressed to the Chairman of the Conference

18 December 1959

Dear Mr. Chairman:

The first meeting of Technical Working Group 2 was convened on 25 November 1959. Twenty-one official sessions of the group, all of them private, were held and work was completed on 18 December 1959.

The Conference members expressed their appreciation to the Secretary-General of the United Nations and to his Personal Representative, Mr. T. G. Narayanan, for the facilities and secretariat services made available to them.

At the second meeting of Technical Working Group 2, 26 November 1959, the agenda of the Conference was adopted, as follows:

1. General statements.
2. Consideration, proceeding from the discussions and the conclusions of the Geneva Conference of Experts, of all data and studies relevant to the detection and identification of seismic events and of possible improvements of the techniques and instrumentation.
3. Consideration of the question of the use of objective instrument readings in connection with the selection of an event which cannot be identified by the international control organ and which could be suspected of being a nuclear explosion, in order to determine a basis for initiating on-site inspections.
4. Preparation of a Report containing conclusions on matters discussed above.

With reference to the approved agenda we note the following: On Item #2 relating to new data and studies, there are areas of disagreement regarding the interpretation of the new data from the Hardtack experiments and regarding the question of de-coupling. Agreement was reached on possible improvements of technique and instrumentation.

On Agenda Item #3 there remain disagreements concerning the use of objective instrument readings in connection with the selection of an event which cannot be identified by the international control organ and which could be suspected of being a nuclear explosion, in order to determine a basis for initiating on-site inspections.

Conclusions on that portion of agenda Item #2 on which agreement was reached are attached to this letter as an annex. Separate reports and comments by separate delegations are also attached to this letter as annexes.

Respectfully,

USSR: (Signed) E. K. Fedorov

UK : (Signed) Sir William Penney

USA : (Signed) J. B. Fisk

ANNEX I

CONCLUSION OF TECHNICAL WORKING GROUP II REGARDING POSSIBLE IMPROVEMENTS OF TECHNIQUES AND INSTRUMENTATION

A. The Technical Working Group has examined the following possible techniques and instrumentation which have the purpose of improving the detection and identification of seismic events:

1. Arrays of seismographs. Arrays of 10 seismographs at each control post were considered and recommended by the Conference of Experts in 1958 in order to increase the signal-to-noise ratio. Experiments since then have confirmed the effectiveness of this method, and the possibility of further improvement by use of even larger arrays of seismographs.

2. Use of long-period surface waves. Experiments since 1958 have shown that this method may assume an important role in the identification of earthquakes. The measurement of long-period waves would be facilitated by including, at all control posts, three-component long-period seismographs with response characteristics optimized for the registration of such waves. These waves will have periods greater than about 10 seconds.

3. Improvement of the operating characteristics of seismic equipment. It may be possible to develop seismographs with more nearly ideal response characteristics, both in the region of long and short periods, to improve the registration of seismic events in the presence of noise.

4. Seismographs in deep holes. The method of using seismographs in holes sufficiently deep to avoid surface noise should be studied further and tested.

5. Spectra of long-period surface waves. Preliminary studies of long-period surface waves show promise that, at a given station, earthquakes may be characterized by a lower dominant frequency than are explosions of the same magnitude in the same area.

6. Other methods of potential interest. There is sufficient theoretical basis for the following methods to justify their further study, but experimental results, although encouraging, are insufficient at present for use to say exactly how they can be used. After some experience and additional research, some of the methods listed below might prove to be of considerable value to the control system.

a. Use of the ratio of the amplitudes of horizontal and vertical waves. The ratio of horizontal amplitude to vertical amplitude of short-period transverse body waves is related to detailed mechanisms at the source. This method could become important if the influence of departures from homogeneity, both at the source and along the propagation path, could be eliminated. There is good reason to expect that the ratio of the amplitudes of long-period waves (for example, Love waves and Rayleigh waves) will be less sensitive to these inhomogeneities, and therefore more effective in revealing the characteristics of the source.

b. Analysis of long-period surface waves. Long-period surface waves were detected at large distances in the case of the underground nuclear explosions Blanca and Logan. In principle, information about the characteristics of the source, relevant to the problem of distinguishing earthquakes from explosions, can be obtained by analysis of these long-period surface waves. Partial success has been achieved in a few experimental investigations of earthquakes and explosions. Until the azimuthal variation of surface waves from different sources has been studied, the significance cannot be determined.

c. Comparison of the shapes of entire longitudinal wave trains received at different stations. This method offers hope of extending capability of direct assessment of first motion. Development of

objective methods of comparison is needed in order to properly evaluate the possible importance of this method.

d. Use of modern data analysis techniques and electronic computing machines. The analysis of seismic waves can be improved by use of modern computing methods, both analogue and digital, including digital recording and processing on calculating machines and certain advanced techniques of modern communication theory.

e. The use of reflected PP and other waves to provide data for the study of the nature of the source of the seismic event.

B. The Technical Working Group recommends, on the basis of the consideration of the possible methods for improvement described in Section A above, that the recommendations of the Conference of Experts for instrumentation at control posts be modified as follows:

1. Installation at all control posts of three-component long-period seismometers of periods greater than ten seconds with the response characteristics optimized for the registration of surface waves in the presence of noise.

2. Increase in the number of short-period vertical seismometers from 10 (as recommended by the Conference of Experts) to 100.

3. The choice of the optimum short-period seismometer as the component of the arrays recommended by the Conference of Experts for purposes of best registration of first motion in the presence of noise.

C. The Technical Working Group recognizes that the recommendations in Section B above represent improvements of instrumentation for the detection and identification of seismic events and that the possible methods considered in Section A may lead to improvements in the future.

D. The Technical Working Group recommends for consideration by the Conference the techniques and instrumentation described above, which have the purpose of improving the detection and identification of seismic events.

ANNEX II

STATEMENT BY THE SOVIET EXPERTS

The Soviet experts examined, jointly with their United States and United Kingdom colleagues, all the material presented to the Technical Working Group. The Soviet experts considered that the Group's main task was, as indicated in its terms of reference, to develop proposals concerning the use of objective instrument readings as a basis for initiating on-site inspections. The Soviet experts believed that a necessary part of their work was to consider possible improvements of techniques nand instrumentation. It was that purpose which the experts thought was to be served by the consideration and discussion of all data and studies relevant to the detection and identification of seismic events. In spite of the clearly defined terms of reference of the Technical Working Group, the United States experts insisted that the Group should also consider the question of estimating the effectiveness of the control system and should revise the estimates made in the report of the 1958 Geneva Conference of Experts. As grounds for revising those estimates, the United States experts cited the "new seismic data" they had submitted. As the Conference knows, the Technical Working Group has adopted an agreed decision on the question of possible improvements of techniques and instrumentation, but failed to arrive at a common view on a combination of objective instrument readings which might serve as a basis for initiating on-site inspections, or on the importance of the "new seismic data" for estimating the effectiveness of the control system. The views of the Soviet experts on certain problems discussed by Technical Working Group 2 are set forth in this statement.

The "new seismic data" were first published in the working paper of 5 January 1959 (document GEN/DNT/25). This document contains the following findings.

> "Stations [used in the Hardtack tests] were all equipped with Benioff short-period vertical seismographs (described in the conclusions of the Geneva Conference of Experts)".
>
> The data obtained in the course of investigation indicate that in the range of yields 0.1 to 23 kilotons the amplitude varies approximately as the first power of the yield of the explosion.

Earlier estimates of the seismic magnitude of the Rainier explosion were too high and new data are given on the magnitude of the Rainier explosion and of explosions in the Hardtack series.

Previous estimates (at the 1958 Conference of Experts) of the number of earthquakes equivalent to explosions of a given yield require revision and should be approximately doubled.

The method of distinguishing earthquakes from explosions by the direction of first motion in the seismic signal is less effective than indicated in the Experts' report.

The annual number of unidentified continental earthquakes equivalent to 5 KT or larger will be greater than that estimates in the Experts' report by a factor of 10 or more.

It must be noted that the document of 5 January provides virtually none of the original, factual data on which its findings are based. The few figures given were obtained by some kind of processing -- generalization, analysis, selection -- of the original data by the author. Fundamentally, the document is a statement, an expression of opinion by the author; and not a summary of original data on the basis of which any other investigators could draw their own oconclusions. As is known, the publication of the 5 January document was the occasion for statements by many political figures of the United States of America and other Western countries -- and particularly by the representatives of the United States and the United Kingdom at the Conference on the Discontinuance of Nuclear Weapon Tests -- to the effect that the control system recommended by the Experts did not actually possess the capabilities laid down by the experts and should be reviewed. There has been a profusion of similar statements in the Western press. Their general theme has been the alleged ineffectiveness of the control system and the need to review the work done by the Experts in 1958.

In the Technical Working Group the United States delegation, in documents and statements, has repeated the findings contained in the working paper of 5 January 1959, with one small modification, viz. the number of earthquakes is raised by a factor, not of 2, but of 1.5.

Having examined the material presented, the Soviet experts have arrived at the inferences and conclusions set forth below.

Instrumentation used in Hardtack tests

During the Hardtack II series of tests, not one of the stations situated in the United States used the array of seismic instruments recommended in the Experts' report. Furthermore, not one of the seismographs used conformed in its parameters to the recommendations in the Experts' report. This is easily established by comparing the parameters of the instruments used with the parameters recommended in the Experts' report (see attached table, pages 12 & 13).

Therefore, the assertion in the working paper of 5 January 1959 that all stations were equipped with Benioff short-period vertical seismographs, allegedly as described in the conclusions of the Geneva Conference of Experts, is a misrepresentation, as the United States delegation itself has virtually admitted.

It is obvious that these other and less efficient instruments could not produce the results that might have been expected if the arrays of seismic instruments recommended by the Experts had been used.

The document of 5 January and the report to the Conference give the impression of a large-scale, well-conducted experiment. In actual fact, the situation was quite different. It was ascertained during the meetings of the Group that of the dozens of seismic stations in the United States, only a small proportion possessed instruments that satisfied, if not the recommendations of the Conference of Experts even the elementary conditions demanded of any scientific instrument. For example, the Logan explosion was registered by 54 seismic stations in the United States. However, only about one half of them (28) had properly calibrated instruments and, in the opinion of the United States seismologists themselves, seismograms from only 16 of these 28 stations could be used for analysis. It is indeed surprising that the instrumentation was not calibrated at least for the period during which these unique experiments were to be conducted.

Modifications of primary magnitudes

Members of the United States delegation delivered to the Group a large number of copies of seismograms. Quite obviously, in the short period of time available, the other delegations were unable to scrutinize and re-measure the amplitudes

recorded, and they asked repeatedly for tables consolidating the source data. These were not supplied by the Americans till the 16th meeting.

The Soviet experts note that United States specialists have repeatedly modified the primary data submitted by them in support of various conclusions. For example, the magnitude of the Rainier explosion was first determined by United States specialists at the end of 1957 and (as reported in United States scientific publications in February 1958) was 4.6. At the 1958 Conference of Experts, United States specialists, stated that the magnitude of 4.6 was incorrect and that the magnitude of the Rainier explosion was actually lower, i.e. 4.25. Finally, in the working paper of 5 January and in reports to the Technical Working Group, United States specialists again reduced this magnitude to 4.07-4.06. The magnitude of the Tamalpais explosion has undergone similar perturbation. In one of the papers submitted by the United States experts at a meeting of the Technical Working Group this magnitude is given as equal to 3.1, and in others to 2.6.

In support of its conclusion concerning the number of times the amplitude of first motion to smaller than the peak amplitude of a seismic signal, the United States delegation submitted its measurements of the amplitudes registered at certain stations. When the Soviet scientists stated that these measurements contradicted the above conclusion, some new values, never previously adduced in the United States documents, were presented at the 19th meeting. After close questioning, it was ascertained that the 0.1 ratio of first-motion amplitude to peak amplitude cited by the United States specialists had not been measured at all at stations in the 2,500-3,500 kilometre zone, although it is on the basis of this very figure that they arrive at some far-reaching conclusions.

Notwithstanding the fact that the initial processing, the preparation for analysis, and the analysis itself, of the seismic data had been done by persons who were United States nationals, the Soviet scientists tried to approach the material before them with the utmost confidence in its reliability, on the assumption that it was the result of careful scientific work. The abovementioned manipulations of the primary data, the erroneous findings in the documents presented by the United States experts, and the fact that the instrumentation used for observing the tests was not in conformity with the 1958 Geneva recommendations have compelled the Soviet scientists to adopt a more cautious attitude towards the quality and objectivity of the figures that were supplied by the Americans.

Estimates of seismic magnitudes of explosions and number of earthquakes equivalent to explosions of given yield

On the basis of the data presented at the 16th meeting it was possible to establish that in the working paper of 5 January 1959, in computing the magnitudes of the explosions, the local magnitude M_L, obtained with the help of torsion seismometers in the first zone (the zone before the shadow zone), had been incorrectly identified with the unified magnitude m, obtained on the basis of observations in the third zone (the zone beyond the shadow zone). In computing the average magnitudes, magnitudes from different scales, M_L and m, were used without being reduced to uniform units. As a result of this, the average magnitudes supplied in the working paper were meaningless. Moreover, in the computation of the average magnitudes, the fact that magnitudes in the shadow zone are consistently undervalued was not taken into account. (This phenomenon in the shadow zone may be attributed to certain physical causes.)

As a result of these and certain other erroneous operations, the working paper of 5 January produced greatly undervalued magnitudes for the Rainier, Logan and Blanca explosions.

The Soviet experts did a more careful analysis of the seismic data on the Blanca and Logan explosions as well as for Rainier. This analysis was based on the well-known work on magnitudes of earthquakes and explosions done by Gutenberg and Richter between 1956 and 1958. As primary data the Soviet experts used all the magnitudes in the first (M_L) and third (m) zones (i.e. exclusive of the shadow zone) which had been presented by the United States delegation at the 16th meeting on 14 December. All of the magnitudes were reduced to the unified scale of m.

As a result, the following magnitudes for the explosions were arrived at:

	Magnitude in working paper of 5 Jan. 1959	Corrected magnitude
Rainier (1.7 KT)	4.07 $\pm$ 0.4	4.7 $\pm$ 0.1
Logan (5 KT)	4.4 $\pm$ 0.4	4.95 $\pm$ 0.1
Blanca (19 KT)	4.8 $\pm$ 0.4	5.2 $\pm$ 0.1

Because of the incorrect magnitudes in the working paper of 5 January and in other documents of the United States experts, the formulation of the relationship between an explosion's magnitude and yield, given at meetings of the working group, was wrong. The more careful analysis of the Soviet experts based on more precise magnitude values results in a different relationship between the magnitude and yield of explosions in the 1.7 - 19 kiloton range.

On the basis of the more precise determination of this relationship and the Gutenberg statistics of 1956, it is possible to estimate the number of earthquakes per year throughout the world which are larger in magnitude than an explosion of given yield. These numbers are presented in the following table, together with the estimates of the 1958 Conference of Experts and the estimates given in the working paper of 5 January.

Yield (KT)	Numbers of earthquakes equivalent to, or larger than explosions of given yield		
	Tentative estimates 1959	Geneva estimates 1958	Working paper of 5 Jan. 1959
1	2	3	4
1	3,000	10,000	26,000
5	1,500	3,800	5,800
10	1,000	2,400	3,000
20	800	1,500	1,600

Thus, on the basis of a more careful analysis of the new seismic data, the Soviet experts have come to the conclusion that the annual numbers of earthquakes throughout the world equivalent to explosions of given yield are, if anything, smaller than the numbers estimated at Geneva in 1958 and not 1.5 or 2 times greater, as is asserted in the United States documents.

For computing the continental earthquakes only, the numbers in the above table must be reduced by a factor of 2.

Sign of First Motion

The assertion in paragraph 9e, of the working paper of 5 January 1959 that "the determination of the direction of first motion is much more difficult than anticipated", the assertion in paragraph 10a of the same document that "the method for distinguishing earthquakes from explosions by the direction of first motion is less effective than previously estimated", and similar statements by the United States delegation on this question in the present conference have not been sufficiently substantiated.

Although all the seismic stations of the special network were equipped only with single Benioff short-period seismographs (and not with arrays of ten of the recommended seismographs) and, what is more, these instruments did not have the magnification of those recommended in the report of the Experts, they nevertheless clearly recorded the first motion as a compression, in the case of the Logan (5 KT) and Blanca (19 KT) explosions up to epicentral distances of 700 km.

If the instrumentation recommended in the Experts' report had been used in the Hardtack experiments, the first motion from the 5 KT explosion could have been clearly registered (with signal exceeding background by a sufficient margin) up to epicentral distances of 1,000 km and, beyond the shadow zone, up to epicentral distances of 3,500 km.

The report of the 1958 Conference of Experts contains the following statement concerning the possibility of distinguishing signals of explosions from those of earthquakes (equivalent to an explosion of 5 KT yield):

> "5. The majority of earthquakes can be distinguished from explosions with a high degree of reliability if the direction of first motion of the longitudinal wave is clearly registered at 5 or more seismic stations on various bearings from the epicentre. Thus not less than 90 per cent of all earthquakes taking place in continents can be identified. The remaining 10 per cent or less of cases will require the analysis of additional seismograms where this is possible; and for this purpose use must also be made of the data of the existing network of seismic stations ..." (EXP/NUC/28, page 11).

This conclusion is by no means refuted but rather confirmed by the measurements taken during the Hardtack experiments, if the quality and characteristics of the instruments used are duly and objectively taken into account.

The raising of the number of seismometers in arrays at each control post from 10 to 100 now being recommended will increase considerably (approximately threefold) the capacity of the control system to determine the direction of first motion in the first longitudinal wave, and this will also permit the identification of explosions of a lower yield.

Significance of the new seismic data

The Soviet experts believe that the seismic observations carried out in connection with the Hardtack tests will certainly be of significance to the work of the control system. They will help the control system to improve its instrumentation and its measurement techniques, as well as in other ways; they will therefore have to be studied most carefully by the control organization staff concerned.

At the same time, and on the basis of careful analysis of all the material presented, the Soviet experts categorically repudiate the way in which primary data have been handled in the document of 5 January and by some members of the United States delegation in the Working Group. Having uncovered many errors as mentioned above, and even some misrepresentation, in United States statements and documents, the Soviet experts note that they all tend in a single direction -- towards reducing the estimates of the control system's effectiveness. The Soviet experts therefore cannot regard these shortcomings as resulting from carelessness or coincidence, and have come to the conclusion that there has been tendentious use of one-sidedly developed material for the purpose of undermining confidence in the control system whose basic characteristics were determined by the 1958 Geneva Conference of Experts.

In this connexion, it must be noted that only the practical utilization of the control system will best permit evaluation of its effectiveness and introduction of improvements as appropriate. Many of the suggestions put before the Working Group by the United States scientists concerning possible improvements in the instrumentation and techniques of the control system can be regarded as correct in principle. Some of them could even now be recommended for practical application. Others may be applicable after a certain amount of experience has been gained in the operation of the control system. Here we would restate what the Experts said in 1958, namely that the use of techniques and instrumentation reflecting the latest scientific developments can always be proposed. Such

innovations will improve the operation of the control system and increase its capabilities. It is clear from this that the next task is not to engage in endless discussion about the potentialities of the control system but to conclude an early agreement on the cessation of tests, establish a control system, and improve it on the basis of practical experience.

Dissimilation of seismic signals of underground explosions

During discussion of the amplitude of the seismic signal produced by an underground nuclear explosion, the United States delegation introduced the idea that the seismic signal could be disguised by carrying out the explosion in a sufficiently deep and large underground cavity. The United States experts' views on the possibility of considerably reducing the seismic signal under such conditions are, in the main, based on general considerations of theory. However, even from the theoretical point of view, the earth's crust is a very complex medium. Therefore, a combination of formal mathematical solutions for the problems involved in the dissimilation of underground explosions does not as yet offer a sound basis for any findings relating to the possible amplitude of the seismic signal generated by an explosion in a deep underground cavity or to the technical feasibility of carrying out vast underground construction operations at a depth of the order of one kilometre.

Objective instrument readings
as a basis for initiating on-site inspections

As the experts concluded in 1958, the control system will record a considerable number of seismic signals from natural earthquakes, some of which it will not be able to identify. Study of an unidentified event may give rise to suspicions and call for investigation at the site of the event. The Technical Working Group should elaborate criteria which would serve as a basis for initiating on-site inspection. As this statement has already indicated, the control system will record thousands of earthquakes equivalent to a yield of 1 - 2 kilotons and above. It is perfectly obvious that criteria must be chosen in such a way that, of this multitude of recorded seismic events, a relatively small number may be selected whose signals are consistent with those of nuclear explosions. Such events may be regarded as suspicious. It is therefore clear that, the more useful the criteria

in permitting the selection of the most suspicious events, the more effective will be the work of the control system. If the control system regards all registered seismic events as equally suspicious, it will never be able to detect real violators.

The 1958 Experts' report already contains clear and definite conclusions concerning the possibilities and methods of distinguishing the seismic signals of earthquakes from those of explosions. The agreed proposals of the Technical Working Group relating to improvements will unquestionably increase the control system's capability of correctly identifying earthquakes of less than 5 KT yield. In this connexion, it would appear that the Technical Working Group was to concentrate its attention on perfecting the criteria previously laid down and on finding new criteria, thereby augmenting the effectiveness of the control system in carrying out its most important function, that of identifying suspicious events and detecting possible violators.

With that purpose in mind, the Soviet experts put forward specific principles for the selection of suspicious events on the basis of findings as to a combination of objective instrument readings.

The basic requirements for determining that seismic events are to be regarded as suspicious can be different in aseismic areas (which represent almost 80 per cent of total continental area), where natural earthquakes are rare and control posts will be widely dispersed, and in seismic areas, where natural earthquakes are very frequent and the network of control posts will be considerably thicker. The Soviet proposals on criteria meet these requirements.

We consider that a seismic event localized within an aseismic continental area of 200 square kilometres (the Experts' report establishes that, with well-defined co-ordinates, a seismic event can be localized within an area of 100 square kilometres) can be regarded as suspicious if there are no clear and definite indications that it has occurred at a depth of tens of kilometres or that it has been accompanied by the characteristic foreshocks and aftershocks of an earthquake.

Thus, the greater part of earthquakes occurring in aseismic areas would, in practice, be regarded as suspicious events.

This approach cannot be used with regard to seismic events occurring in seismic areas, where there are thousands of earthquakes per year. However, only some of them produce signals similar to those of nuclear explosions. The great density of the control post network in seismic areas will make it possible to ascertain reliably differences in the nature of seismic signals. For this purpose, it will be necessary to utilize the distinguishing characteristics previously ascertained and some of those now proposed. Specifically, the Soviet representatives proposed the use of the sign of first motion of the seismic signal (the effectiveness of which was ascertained by the Experts in 1958), as well as certain new indicators.

Such an approach will unquestionably ensure the detection of truly suspicious events, on which the control system's future activity will be concentrated.

The approach of the United States delegation is completely different. On the basis of the wrong conclusions already referred to and notwithstanding the facts, the United States experts suggest a system of criteria which virtually rejects the very idea of selecting suspicious events from the events recorded by the control system.

As a result of analysis, it became clear, for example, that if the United States criteria were used the determination of first motion could be considered basically reliable only in the case of explosions with yields of the order of hundreds or thousands of kilotons. Obviously, such a formulation of criteria is challenged even by the United States interpretation of the Hardtack measurements.

According to the United States scientists themselves, their criteria would leave under suspicion the overwhelming majority of the earthquakes registered by the control system.

The Soviet experts submit that here their United States colleagues are on the brink of absurdity.

* * *

In concluding this statement, the Soviet experts note that, in spite of the significant differences that still remain, the meetings of the Technical Working Group had a positive result, as is shown by the adoption of an agreed decision regarding improvements of techniques and instrumentation, which can increase the effectiveness of the control system.

TABLE

Comparison of parameters of control-post seismic apparatus as determined in report of 1958 Geneva Conference of Experts, with parameters of seismic apparatus used in Hardtack tests

Types of instruments and parameters required	Parameters of instruments used in Hardtack tests	Shortcomings in observations resulting from failure of parameters to meet requirements
1. Short-period vertical seismographs		
(a) Approximately 10 should be dispersed over a distance of 1.5 - 3 kilometres	Not one station was equipped with recommended number of seismographs, dispersed and connected as required for best signal to noise ratio and clear registration of first motion. Stations were equipped with only single vertical seismograph. Recommended method of arrays was used in only two cases, and then only 4 seismographs were installed.	Effective capacity to detect signal was considerably reduced; this led to wrong registration of first motion at some stations. In the two cases where arrays were used, even with only 4 seismographs a considerably greater ratio of signal amplitude to interference amplitude was obtained.
(b) Should have a maximum magnification of the order of 10^6 at a frequency of 1 c.p.s.	Seismographs had maximum magnification at a frequency of 3 c.p.s. Magnification of instruments was not raised to 10^6.	Maximum frequency response of seismograph did not fit maximum spectrum of signal when recorded in the third zone. Optimum recordings were therefore not obtained.

TABLE (contd.)

Types of instruments and parameters required	Parameters of instruments used in Hardtack tests	Shortcomings in observations resulting from failure of parameters to meet requirements
(c) Should have a receiving band adequate to reproduce the charac teristic form of the seismic signal.	Relevant receiving band of Benioff seismograph was, from level of 0.7, approxi mately of order of two, whereas a broader receiving band is needed for accurate reproduction of form of seismic impulse.	Since receiving band of instruments was optimal, seismic signals were recorded with strong distortions, so that there was considerable reduction of ratio of first motion amplitude to peak amplitude of seismic signal. Consequently, results in registration of first motion obtained during tests were less satisfactory than might have been expected.
2. Horizontal seismographs with the parameters indicated in point 1.	These seismographs were used at some stations.	
3. One three component installation of long period seismographs having a broad receiving band and a con stant magnification of the order of 10^3 - $2x10^3$ in the period range 1 - 10 seconds.	These seismographs were not used at a single station.	The vertical seismographs of this combination, if used as recommended, would have ensured correct reproduction of form of seismic signal without reducing amplitude of first motion. Under favourable noise conditions, registration of sign of first motion on these seismographs should have yielded incomparably better results.
4. One three component installation of seismographs with magnification of the order of 10^4 - $2x10^4$ where T = 2 - 2.5 seconds.	These seismographs were used in only four cases.	In combination with other instrumentation these seismographs could have provided supplementary data for identification.

ANNEX III

REPORT BY THE UNITED KINGDOM DELEGATION
FROM THE PROCEEDINGS OF TECHNICAL WORKING GROUP II

(1) The United Kingdom has no seismological data of its own on the underground explosion RAINIER or on the underground explosions of the HARDTACK series. The United Kingdom has not exploded a nuclear device underground.

(2) The United Kingdom Delegation agrees with the Delegations of the Union of Soviet Socialist Republics and the United States of America on the material given in the first Annex. [Conclusion of Technical Working Group II regarding possible improvements of techniques and instrumentation].

(3) With regard to HARDTACK data on first motion, the opinion of the United Kingdom Delegation is stated as follows.

The 1958 Conference of Experts concluded that the majority of earthquakes can be distinguished from explosions with a high degree of reliability if the direction of first motion of the longitudinal wave is clearly registered at five or more stations. They also stated that, using their recommended array of seismometers at each control post, the direction of first motion would be clearly observed from weapons greater than 5 kT. over a range of distances from 2,000 to 3,500 km. from the weapon, even in periods of unfavourable noise conditions. This was the only instrumental criterion specifically mentioned by the Experts and was considered by them to be sufficiently powerful to identify not less than 90 per cent of all continental earthquakes.

The United Kingdom Delegation believes that the HARDTACK data have shown that the 1958 Experts were too optimistic. For example, we have been impressed by the fact that only one station out of six in the third zone (2,509 km. to 3,590 km.) in the case of BLANCA (19 kT.) gave a clearly recognizable compressional first motion. Whilst it is true that these observations were made with single BENIOFF instruments, the use of arrays of ten such instruments can be expected to have given one

positively identified compressional first motion out of six stations from an explosion of 4 kT. yield in the environment of the BLANCA explosion. The use of 100 seismometers in each array, together with possible improvements in the individual instruments, would certainly increase the proportion of the stations in the third zone able to identify positively compressional first motion; but to what extent is not yet clear. Since the stations in the third zone are of prime importance for collecting first motion data, the United Kingdom Delegation consider that even with arrays of 100 seismographs of improved design, it is unlikely that the stations in the third zone will have a high probability of being able to show a positively identified compressional first motion from an explosion of 5 kT. in RAINIER conditions.

The HARDTACK data have been criticized on the grounds that the BENIOFF seismographs used in the experiment did not comply with the specification of the 1958 Conference of Experts. However, the United Kingdom Delegation accepts the demonstration given by the United States Delegation that the characteristics of the BENIOFF instrument are such that the fact that it did not comply with the specification would not make it inferior for the registration of the first motion in the presence of seismic noise.

The maximum amount of information must be extracted from the basic data of RAINIER and HARDTACK because these are the only underground nuclear explosions for which we have results.

(4) With regard to the number of earthquakes per year in the world equivalent to or greater than underground explosions of a given yield, the United Kingdom Delegation have the following views.

The Geneva Conference of Experts in 1958 had available to them the data from only one underground nuclear explosion (RAINIER). As a result of the HARDTACK series, more data have become available. Using all of these data, we estimate that each year throughout the world there will probably be between 1,000 and 4,000 shallow earthquakes equivalent to 20 kT. or more, between 2,500 and 10,000 equivalent to 5 kT. or more,

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and between 7,500 and 30,000 equivalent to 1 kT. or more. The spread in these figures reflects our uncertainties about the seismic signals generated by underground nuclear explosions, and also our ignorance of the worldwide distribution of small earthquakes.

We think that it is important to appreciate the large range of uncertainty in these numbers.

(5) With regard to the possibility of greatly reducing the seismic signals by exploding a nuclear weapon in a deep underground cavity, the views of the United Kingdom Delegation are as follows.

Theory shows that the seismic signal generated by a nuclear explosion in an underground cavity can be much less than that from an equal explosion in RAINIER conditions. The theory assumes that the cavity is sufficiently large and deep for the material around the cavity, right up to the boundary surface, to behave elastically. Calculations indicate, for example, that a cavity in salt, one kilometer below ground level, of volume 7×10^4 m^3 per kiloton, should suffice to meet the theoretical requirements.

The theory assumes a perfect isotropic medium, and makes certain assumptions about the stress distribution around the cavity before the explosion occurs. Careful work would have to be done before it could be stated that conditions likely to be met in practice do not require the theory to be modified. However, it may well be possible in practice, should the necessary scientific research and engineering effort be found, to give confidence that a decoupling factor of two orders of magnitude compared with RAINIER conditions could be achieved.

Experiments have been made to compare the seismic signals at about one mile from high explosive charges, exploded in an underground cavity, with those given by smaller charges placed a few feet from the cavity in the surrounding limestone. Approximately ten times as much explosive was required in the cavity as in the surrounding limestone to give equal seismic signals. A decoupling factor of about one order of magnitude in limestone has thus been demonstrated for one cavity which was smaller

and less deep than those demanded by the above-mentioned theory.

Cavities are known to exist in salt formations which would satisfy the volume and depth requirements for a few kilotons. The cavities are not spherical shape and the stress distributions around the cavities are not known.

(6) The Soviet Delegation suggested criteria which would separate off a relatively small class of events which they consider eligible for inspection. In our opinion, explosions of several tens of kilotons would be correctly classified by these means; but small explosions would, with high probability, be misidentified as earthquakes.

The United States Delegation suggested criteria which will identify most large earthquakes, but leave the majority of seismic events unidentified and hence eligible for inspection.

We accept the value of the American and Soviet criteria on depth of focus and epicentral location in deep oceans. We think that the criteria on foreshocks and aftershocks are useful ones and we also approve the proposed criterion about eligibility for inspection based on the location of the epicentre in an aseismic area.

With regard to the location of an epicentre, we consider that when reliable travel time curves have been established, it should be possible to locate an event to within an area of 200 square kilometers, except near a coastline. National seismic stations can give valuable help in determining travel time curves.

In addition to the main criteria based on first motion, the American and the Soviet Delegations have suggested a number of phenomena and methods capable of giving auxiliary information. These may be called aids to criteria. We believe that these aids can appreciably increase the value of the choice of an inspection over that of random choice. We are hopeful that some of them may be capable of being codified into valuable criteria at some time in the future, when the necessary research has been done. However, we cannot at present see how any of these aids can be codified, and we do not believe that at present any of them has

the element of reliability that a criterion must have.

Thus the difficulty in which we find ourselves is that we cannot at present propose criteria which will identify a large proportion of earthquakes as such. A large number remain unidentified and must therefore be considered as eligible for inspection. Aids are not yet in a codified form or sufficiently reliable to be used as criteria but they do have real value as statistical weighting factors.

In our opinion, the best that can be done in the present state of knowledge is to define criteria which will identify a modest proportion of earthquakes. The remaining events must be regarded as eligible for inspection, even though the number of events will, for a few years, be far too large for all to be inspected. However, world research on seismology, including work done by the control organ itself, could in a few years materially increase the proportion of earthquakes which can be identified.

It is for the Political Conference to consider the procedure by which the aids to criteria might be introduced as weighting factors and the procedure by which the events to be inspected are chosen.

(Signed) W. G. Penney
Head of United Kingdom Delegation
to Technical Working Group II.
Geneva. December 18, 1959.

ANNEX IV

REPORT OF THE DELEGATION OF THE UNITED STATES CONCERNING TECHNICAL WORKING GROUP II OF THE CONFERENCE ON THE DISCONTINUANCE OF NUCLEAR WEAPONS TESTS

A. The Conference on the Discontinuance of Nuclear Weapons Tests on 24 November 1959 agreed upon terms of reference for Technical Working Group II as follows:

"The Technical Working Group of experts shall consider the question of the use of objective instrument readings in connection with the selection of an event which cannot be identified by the international control organ and which could be suspected of being a nuclear explosion, in order to determine a basis for initiating on-site inspections. As part of their work, the experts, proceeding from the discussions and the conclusions of the Geneva Conference of Experts, shall consider all data and studies relevant to the detection and identification of seismic events and shall consider possible improvements of the techniques and instrumentation."

B. The Delegation of the United States to Technical Working Group II concludes on the basis of its consideration, proceeding from the discussions and the conclusions of the Geneva Conference of Experts, of all data and studies relevant to the detection and identification of seismic events as follows:

1. On the basis of the Hardtack data, the amplitude of first motion of P-waves is smaller than was concluded on the basis of data available to the Conference of Experts. Because of the small amplitude of first

motion and the presence of noise, the first motion from an explosion will sometimes appear to be a rarefaction at distances up to 1100 kilometers and also beyond 2500 kilometers. The vertical component seismograms obtained during the Hardtack operation showed numerous apparent first motions corresponding to rarefactions. The direction of the first motion is also unreliable in the "shadow zone" which was shown by Hardtack data to extend from about 1100 to 2500 kilometers, instead of 1000 to 2000 kilometers as was concluded at the Conference of Experts. As a result of these new data concerning first motion, we conclude that the direction of first motion which the Conference of Experts considered to be the only specific criterion for identifying earthquakes is useful only at substantially higher equivalent yields than was concluded by the Conference of Experts.

2. The amplitudes of seismic signals produced in the Hardtack Series were smaller than would have been estimated on the basis of the data available to the Conference of Experts. We estimate that each year there will be throughout the world be about 2000 shallow earthquakes equivalent to 20 KT or more, about 5000 equivalent to 5 KT or more, and about 15,000 equivalent to 1 KT or more. However, our knowledge of the frequency of occurrence is uncertain by at least a factor of two either way. It is expected that variations of location, medium, and depth of the explosion will also produce

considerable variation of the amplitude of the seismic signal from a closely confined explosion of a given yield. Our estimated number differs from the number which could have been estimated on the basis of the data available to the Conference of Experts by less than the uncertainties mentioned above.

3. Theory now indicates that the amplitude of the seismic signal produced by an underground explosion at large distance should vary with the first power of the yield up to at least 20 KT. For sufficiently greater yields theory shows that the signal should vary as the 2/3 power of yield. The best fit with a single power law to the Rainier and Hardtack data, including explosions in the 100-ton range, is provided by an exponent of 0.9 ± 0.1. Consideration of Rainier, Logan and Blanca (1.7 to 19 kilotons) alone would indicate an 0.7 ± 0.1 power law.

4. The Hardtack tests show that strong horizontally polarized transverse waves (SH) and long-period Love waves are excited by underground explosions. Therefore, such waves cannot be considered characteristic only of earthquakes.

5. Rigorous theoretical calculations combined with measurements on the Rainier explosion show that the seismic signal produced by an explosion in a sufficiently large underground cavity in salt or hard rock will be reduced by a factor of 300 or more relative to the seismic signal from an explosion of the same yield under Rainier conditions. Calculations indicate that a cavity at a depth of about one kilometer with a volume of 7×10^4 cubic meters per kiloton should suffice.

Cavities are known to exist in salt formations which would satisfy the volume and depth requirement for explosions of several kilotons. Engineering studies indicate that it is feasible to construct cavities which would satisfy the volume requirement for explosions at least as large as 70 kilotons. The total construction time for a cavity of this size in a salt dome is estimated to be from 2 to 4 years.

C. The Delegation of the United States concurs with the conclusions and recommendations of Technical Working Group 2 regarding possible improvements of techniques and instrumentation which have the purpose of improving the detection and identification of seismic events. These agreed conclusions and recommendations are set forth in the following paragraphs C, 1 through C, 4:

1. The Technical Working Group has examined the following possible techniques and instrumentation which have the purpose of improving the detection and identification of seismic events:

   a. Arrays of seismographs. Arrays of 10 seismographs at each control post were considered and recommended by the Conference of Experts in 1958 in order to increase the signal-to-noise ratio. Experiments since then have confirmed the effectiveness of this method, and the possibility of further improvement by use of even larger arrays of seismographs.

   b. Use of long-period surface waves. Experiments since 1958 have shown that this method may assume an important role in the

identification of earthquakes. The measurement of long-period waves would be facilitated by including, at all control posts, three-component long-period seismographs with response characteristics optimized for the registration of such waves. These waves will have periods greater than about 10 seconds.

c. Improvement of the operating characteristics of seismic equipment. It may be possible to develop seismographs with more nearly ideal response characteristics, both in the region of long and short periods, to improve the registration of seismic events in the presence of noise.

d. Seismographs in deep holes. The method of using seismographs in holes sufficiently deep to avoid surface noise should be studied further and tested.

e. Spectra of long-period surface waves. Preliminary studies of long-period surface waves show promise that, at a given station, earthquakes may be characterized by a lower dominant frequency than are explosions of the same magnitude in the same area.

f. Other methods of potential interest. There is sufficient theoretical basis for the following methods to justify their further study, but experimental results, although encouraging, are insufficient at present for us to say exactly how they can be used. After some experience and additional research, some of the methods listed below might prove to be of considerable value to the control system.

(1) Use of the ratio of the amplitudes of horizontal and vertical waves. The ratio of horizontal amplitude to vertical amplitude of short-period transverse body waves is related to detailed mechanisms at the source. This method could become important if the influence of departures from homogeneity, both at the source and along the propagation path, could be eliminated. There is good reason to expect that the ratio of the amplitudes of long-period waves (for example, Love waves and Rayleigh waves) will be less sensitive to those inhomogeneities, and therefore, more effective in revealing the characteristics of the course.

(2) Analysis of long-eriod surface waves. Long-period surface waves were detected at large distances in the case of the underground nuclear explosions Blanca and Logan. In principle, information about the characteristics of the source, relevant to the problem of distinguishing earthquakes from explosions, can be obtained by analysis of these long-period surface waves. Partial success has been achieved in a few experimental investigations of earthquakes and explosions. Until the azimuthal variation of surface waves from different sources has been studied, the significance cannot be determined.

(3) Comparison of the shapes of entire longitudinal waves trains received at different stations. This method offers hope of extending capability of direct assessment of first motion. Development of objective methods of comparison is needed in order to properly evaluate the possible importance of this method.

(4) Use of modern data analysis techniques and electronic computing machines. The analysis of seismic waves can be improved by use of modern computing methods, both analogue and digital, including digital recording and processing on calculating machines and certain advanced techniques of modern communication theory.

(5) The use of reflected PP and other waves to provide data for the study of the nature of the source of the seismic event.

2. The Technical Working Group recommends, on the basis of the consideration of the possible methods for improvement described in Para.C.1 above, that the recommendations of the Conference of Experts for instrumentation at control posts be modified as follows:

a. Installation at all control posts of three-component long-period seismometers of periods greater than ten seconds with the response characteristics optimized for the registration of surface waves in the presence of noise.

b. Increase in the number of short-period vertical seismometers from 10 (as recommended by the Conference of Experts) to 100.

c. Choice of the optimum short-period seismometer as the component of the arrays recommended by the Conference of Experts for purposes of best registration of first motion in the presence of noise.

3. The Technical Working Group recognizes that the recommendations in Para. C.2 above represent improvements of instrumentation for the detection and identification of seismic events and that the possible methods considered in Para. C.1 may lead to improvements in the future.

4. The Technical Working Group recommends for consideration by the Conference the techniques and instrumentation described above, which have the purpose of improving the detection and identification of seismic events.

D. The Delegation of the United States to Working Group 2 concludes that any seismic event, located as described in Paragraph D.1 below, could be suspected of being an underground nuclear explosion and therefore should be eligible for inspection unless it meets or or more of the specific criteria enumerated in Paragraph D.2 below which identify the event as an earthquake. A seismic event occurring in an aseismic area is to be considered eligible for inspection even if it meets the criteria of Para. D.2 (d) below. For this purpose an aseismic area is to be considered as any area at a distance of more than 100 kilometers from the epicenter of a located earthquake of magnitude 4.4 or greater.

1. Location of Seismic Events

A seismic event shall be considered to be located when seismic signals, whose frequencies, amplitudes, durations, and velocities are consistent with those of waves from earthquakes or explosions, are recorded at a sufficient number of control posts to establish the approximate time and position of the event. This requires at least 4 clearly measurable arrival times of identifiable phases which are mutually consistent to within $\pm$ 3 seconds. These 4 consistent arrival times must include P-wave arrival times at 3 different control posts.

If the event is eligible for inspection, the area eligible for inspection consists of that 500 square kilometers which has the highest likelihood of containing the epicenter, according to a previously established data reduction procedure. This procedure

shall take into account the frequent occurrence of relatively aberrant observations and the relative accuracies of different observations. When adequately precise regional travel time curves are developed and used, and consistent arrival times are available from control posts surrounding the epicenter, that is, from control posts at least one of which lies in every possible 90° sector around the epicenter, the area eligible for inspection will be the 200 square kilometers which has the highest likelihood of containing the epicenter.

2. Identification of Earthquakes

A located seismic event shall be ineligible for inspection if, and only if, it fulfils one or more of the following criteria:

a. Its depth of focus is established as below 60 kilometers;

b. Its epicentral location is established to be in the deep open ocean and the event is unaccompanied by a hydroacoustic signal consistent with the seismic epicenter and origin time;

c. It is established within 48 hours to be a foreshock by the occurrence of a larger event of at least magnitude 6 whose epicenter coincides with that of the given event within the accuracy of the determination of the two epicenters. The eligibility of the second event for inspection must be determined separately.

d. The directions of clearly recorded first motions define a pattern which strongly indicates a faulting source. First motions recorded at distances between 1100 kilometers and 2500

kilometers will not be used. First motions beyond 3500 kilometers will not be used for events of magnitude smaller than 5.5. The apparent direction of first motion must also meet both the following minimum conditions to be considered to be clearly recorded:

(1) The amplitude of the half-cycle of apparent first motion is at least two (2) times as large as any half-cycle of apparent noise in the preceding few minutes, and

(2) The largest of the amplitudes of the half-cycle of apparent first motion and the two immediately following half cycles:

(a) at epicentral distances less than 700 kilometers is twenty (20) times larger than any half-cycle of noise in the preceding few minutes,

(b) at epicentral distances more than 700 kilometers is forty (40) times larger than any half-cycle of noise in the preceding few minutes.

A pattern of clearly recorded first motions strongly indicates a faulting source if the observed motions, extended backward to a small sphere about the focus, can be separated into alternate quadrants by two orthogonal great circles drawn on the small sphere, with the requirement that two opposite quadrants combined (i) contain at least 4 clearly recorded rarefactive first motions and (ii) contain not more than 15% compressions among the clearly recorded first motions.

First motion criteria cannot properly be defined without specifying the seismograph used. In this connection the description of the short-period vertical seismographs which make up the arrays of 10 described by the Conference of Experts has to be expanded as follows: the instruments will be optimized to detect first motion in the field of noise known to exist in the earth and the receiving band will be selected to balance the need to reproduce the characteristic form of the seismic signal against the need to reject the noise, and will be such as will permit operation of single seismographs at quiet stations with a magnification greater than 10^6 at the frequency of peak response. These conditions are presently judged to place the frequency of peak response somewhere between 1 and 5 cycles/sec.

e. It is established to be an aftershock of a seismic event of at least magnitude 6 which has been clearly identified as an earthquake by the criteria in Pars. D.2. a,b, or d. For this purpose an aftershock is defined as one of a sequence of earthquakes which occurs less than one week after the main shock and which has an epicenter within 10 kilometers of the epicenter of the main shock.

3. The basic data for all criteria will be obtained from the control posts. Supplementary data not involved in determining the eligibility of a particular event for inspection may be derived from

national stations; for example, readings from national stations might be used to establish the regional travel time curves as described in Para. D.1.

E. The criteria described above in Section D, which make certain detected and located seismic events ineligible for inspection, leave a large number of seismic events eligible for inspection. Selection of certain eligible events for inspection may be made more effective by the use of auxiliary seismological information, so long as this information is used only as an aid to selection, and is never allowed, by its own weight, to exclude the possibility that a particular event will be inspected. At the present state of seismological knowledge, the effectiveness of selection would be very greatly reduced if any rigid or formal procedure of using such auxiliary information were adopted. Such auxiliary information may include the following seismic phenomena:

1. Even if an event remains eligible for inspection in accordance with the criterion of Paragraph D.2.d. above, first motion phenomena may provide auxiliary information. Specifically, both (a) patterns of first motion consistent with a faulting source, and (b) rarefactional first motions at stations where the signal-to-noise ratio is high, are suggestive of natural earthquakes.
2. Surface wave phenomena can provide auxiliary information, particularly in view of their large amplitudes in comparison with first movements of the longitudinal wave. Specifically, the following are suggestive of natural earthquakes:

a. inferred near-source behavior of Rayleigh waves consistent with a faulting source;

b. high ratios of Love wave amplitude to Rayleigh wave amplitude at a number of stations at wisely different azimuths from the source;

c. predominant frequencies of Love waves equal to or less than the value typical of earthquakes of the same magnitude recorded over a similar path;

d. predominant frequencies of Rayleigh waves equal to or less than the value typical of earthquakes of the same magnitude recorded over a similar path;

e. unusually large amplitude of long-period surface waves in comparison to that expected of an explosion of the same magnitude, and

f. strong dependence of long-period Rayleigh wave amplitudes on azimuth of observation.

3. The following also provide auxiliary information suggestive of a natural earthquake.

a. a sequence of many after-shocks;

b. large ratios of SH to SV amplitudes at many and widely different azimuths from the source;

c. a seismogram duplicating in detail a seismogram from a known earthquake with coincident epicentar; and

d. seismic waves, particularly surface-reflected body phases, indicative of a focal depth of tens of kilometers.

4. For the Nevada underground explosions and many earthquakes, at distances beyond 2500 kilometers the ratio of second-to-first motion appears to be several times larger, on the average, than the ratio of third-to-second motion. This fact may be useful in evaluating the direction of first motion, since on a given seismogram the earliest motion of a size comparable with that immediately following, would then be likely to be the actual second motion. The variations in the ratios of second-to-first and third-to-second motion are large, and explosions in other situations may produce seismic waves of quite different amplitude ratios, so that the power of this method cannot be evaluated at this time.

It is not possible at the present time to devise a formal procedure for the use of this auxiliary information, nor is it possible to use it as a means to eliminate the eligibility of any particular event for inspection. However, some of the seismic characteristics listed above may, in the future, develop into criteria to establish an event as natural in origin. The formulation and establishment of future criteria using such characteristics can only be carried out on the basis of continuing research. This research is likely to involve observations at many locations of earthquakes and, in some cases, of large explosions, the development of instruments, and the use of modern data processing techniques.

ANNEX IV

APPENDIX

Comments by the Delegation of the United States Regarding the "Report of the Delegation of the United States concerning Technical Working Group 2 of the Conference on the Discontinuance of Nuclear Weapons Tests"

In accordance with the Terms of Reference, the United States Delegation bases its report on all scientifically valid conclusions concerning the detection and identification of nuclear events based on new studies and data, whether such conclusions would lead to improvements of the system or would lead to an assessment which would make the system appear less effective. It is the view of the United States Delegation that mentioning only the potential improvements in its final conclusions on this subject would mislead the Conference on the Discontinuance of Nuclear Weapons Tests concerning the present technical status of the possible control system.

One of the important conclusions in Section B of the report deals with the so-called "first motion" problem, that is the direction in which a seismic needle would swing as a first response to a seismic disturbance. This direction was considered by the Conference of Experts to be the primary tool for discriminating between earthquakes and explosions. The conclusion drawn by the United States Delegation based on new data is that this method of discrimination is much less effective than had been thought.

A further important conclusion in this section concerns the possibility of concealment of underground nuclear explosions by detonating such an explosion in a very large underground cavity

in salt or hard rock. It was shown theoretically that the seismic signal of a given explosion under these conditions could be reduced three hundredfold or more as compared to the signals produced in the Nevada tests. Consequently explosions could be made to look smaller by this factor and thus be much harder to detect and locate.

An item in Section B deals with the estimate of the number of earthquakes which would be expected to be detected and located by the control system. The conclusion is that the estimates of such a number are very uncertain but that about 15,000 earthquakes per year would be located by this system over the whole world, corresponding to earth movements produced by nuclear explosions of more than one kiloton. For larger explosions such as 20 kilotons, the number of equivalent earthquakes is about 2,000 worldwide.

All Delegations concurred in Section C, which contains a list of new seismological techniques which could in the future be used to improve the control system. Our knowledge of these techniques ranges from very detailed to purely speculative, but it is clear that further research work will demonstrate the degree of utility which these techniques and improvements of instrumentations may have on the control system. As a result of these studies, the delegations were able to agree on specific recommendations for instrumental improvements of the control system as listed in Section C.

Section D describes "criteria based on objective instrument

readings" which could be used by the control organization in determining the eligibility of detected and located seismic events for inspection. Agreement was not reached on this section. It is the view of the U. S. Delegation that such criteria must be formulated so that a large number of explosions would not be classified as natural earthquakes and that the criteria must be based on well established technical information. Unfortunately, the resulting criteria classify only a small fraction of the seismic events as natural earthquakes leaving a large number eligible for inspection. It was the view of the USSR Delegation that criteria must be specified by this Working Group which would remove a large fraction of the seismic events from eligibility for inspection by identifying them as natural earthquakes. However, it is the view of the U. S. Delegation that this is impossible within present technical knowledge. In fact the criteria proposed by the USSR Delegation would have classified such events as the recent U. S. underground nuclear test explosions which range up to 19 kilotons in yield as natural earthquakes and thus would have made them ineligible for inspection. It is the view of the U. S. Delegation that as scientific knowledge progresses, more useful criteria can be formulated in the future.

The U. S. Delegation recognizes that there is a great deal of additional seismic information available, as listed in Section E, which is not sufficiently complete to be formulated

into specific criteria. The U. S. Delegation feels that such auxiliary information should be very useful if evaluated in a competent technical manner in connection with a particular seismic event.

In the veiw of the U. S. Delegation, the problem of the formulation of criteria is a strictly technical problem. If technical knowledge permits one to identify a large fraction of seismic events as earthquakes, then it is clearly a great advantage to the control system. If technical knowledge does not permit this, then seismic events must remain eligible for inspection. Determination of the means of selecting events to be inspected must be left for further consideration by the Conference.

APPENDIX 5

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THE NEED FOR FUNDAMENTAL RESEARCH IN SEISMOLOGY

Report of the

PANEL ON SEISMIC IMPROVEMENT

Lloyd V. Berkner, Chairman
Hugo Benioff
Hans A. Bethe
W. Maurice Ewing
John Gerrard
David T. Griggs
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March 31, 1959

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I - SUMMARY REPORT

1. Introduction

An earthquake or underground nuclear explosion excites seismic waves which propagate into the earth's interior and emerge again at a continuous succession of distances from the source. These waves, which are not unlike sound waves, may be recorded with seismographs distributed over the surface of the earth. The characteristics of records written by seismographs depend on the nature of the source and effects of earth structure on the seismic waves. The fundamental problems of seismology are to infer separately the nature of the seismic source and the conditions in the earth's interior from analysis of a set of seismograms.

The problems of detection and identification of underground nuclear explosions have focused attention on the need for increased support of seismological research. At present (neglecting private research in petroleum exploration geophysics, most of which does not apply to the present problem), the annual budget in the United States from all sources for seismological research amounts to roughly several hundred thousand dollars. This supports investigations at a modest level of the earth's internal constitution and limited analytical studies on seismic wave propagation. Research at this level and less over the last half century has been sufficient to delineate the major elements of the earth's internal constitution and to explain many features of seismograms. We have learned that the earth has a solid inner core surrounded by a liquid outer core, a solid mantle and a crust which thickens and thins in response to variations in topographic load. We can locate earthquakes and explosions and distinguish between them if they are large. However, seismologists have long recognized that major advances in their field could be realized only if the level of research were significantly increased. Then more physicists, mathematicians and engineers could be brought into the field, and modern computing machine methods of data reduction and analysis could be more fully exploited.

It is obvious that progress in the field of seismic detection is inseparable from advances in the major subdivisions of seismology. Thus, the identification of earthquakes as events distinct from explosions requires knowledge of earthquake mechanisms. The fine details of the internal constitution of the earth must be known, and analytical methods must be found to determine the effect of propagation

in the earth on the character of seismic waves. The nature of microseisms must be understood before optimum methods of increasing signal-to-noise are realizable. All of these examples, where advances in fundamental seismology bear significantly on the detection problem, represent fields which seismologists would choose to emphasize even if there were no need for improvements in seismic detection.

The USSR in recent years has emphasized seismological research to such an extent that the Soviets enjoy a position superior in many respects to our own. In the field of sounding the earth's crust by means of small explosions, as one example, Soviet annual expenditure on crustal studies has been estimated by visiting American scientists to be about $1,000,000, in contrast to a budget of perhaps $100,000 for such crustal studies in the U.S.A. Comparison of recent USSR and U.S.A. publications in this field clearly reflect the resulting higher level of Soviet work.

The strategic requirements of detection, together with the need to maintain a competitive position in one of the most significant fields in the earth sciences make it a matter of urgency to institute a high level of support of seismological research. Various phases of seismology which have special priority are reviewed in this report, briefly in this summary, and more fully in appendices. e treat, in that order, conditions at the source, effects of transmission through the earth, instrumentation for recording seismic signals, and certain suggestions for more sophisticated processing of the recorded data.

2. Source Phenomena

We hope to learn, from seismic evidence, how to distinguish between natural earthquakes and explosions, at least in the great majority of cases. If we are to do this, it is essential that we improve our knowledge of the phenomena associated with the various types of sources of seismic waves. We need to know more about the mechanism of seismic wave generation when the source is a nuclear or chemical explosion, but it is equally important, perhaps more so, to understand the mechanisms of all kinds of natural earthquakes.

Our present state of knowledge in this field results from a variety of approaches, all of which have been explored to only a minor degree. The radiation pattern from the source has been studied for, at most, a few hundred earthquakes, the majority of which were large shocks recorded throughout the world. The raw data for such studies

always suffer from inadequate, non-uniform instrumentation. Further studies, based on large shocks and on a world-wide network with improved instrumentation (1)*, should be conducted to improve our understanding of the fundamental tectonic processes in the earth. It is equally important to conduct studies of the radiation pattern (2) on a smaller scale in seismic localities. Semi-permanent installations (3) should be concentrated in a region of known seismicity, operated until sufficient data on shocks in the region are obtained, then moved to a new locality. Data collected in such a manner would provide information, not only on the radiation pattern of the source, but also on the depth of focus and on aftershock sequences (4).

Depth of focus is difficult to determine with sufficient precision using present techniques, largely because of insufficient density of seismographs. If adequate data can be obtained on focal depth for a number of shocks in different regions, it may then be possible to find other methods of determining depth using seismograms from more widely spaced stations. The Panel recommends a thorough investigation of such possibilities.

Aftershock sequences are important because they provide a possible means of identifying earthquakes, and because the pattern of aftershocks, with regard to magnitude, location and fault motion, is of great importance to our understanding of the forces which cause earthquakes. An appropriate field program is recommended.

Theoretical studies relating to source phenomena should parallel, and in some cases be closely related to, the field programs. The existing theory is largely limited to elementary concepts of explosive and faulting sources. New studies on the excitation of body waves and surface waves of all significant modes of propagation (5,6) should be conducted, which take into account non-linear effects near the source, effects of variation in the surrounding medium, effects of heterogeneity in the region of the source, effects of finite fault length, and effects of depth and fault mechanism.

Model studies should be used to supplement both the field programs and the theoretical programs. In addition to the conventional untrasonic techniques using transducers as repetitive sources, small scale explosive sources would, on occasion, provide valuable data.

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*Numbers in parentheses refer to Appendices.

When the quality of seismic instrumentation is improved throughout the world, or even within a small seismic region, it will be possible to re-evaluate our present techniques for assigning magnitudes to seismic disturbances, and especially for improving the relationship between magnitude and energy release. It is distressing that, as a result of present instrumental limitations, seismologists are unable to fix such a fundamental physical quantity as the seismic energy release in an earthquake within a factor of 10 or more.

Whenever there is evidence of surface faulting or other macroseismic phenomenon, field studies should be made in an attempt to relate observable effects near the source with propagating seismic disturbances. Itensity data should be included as well as related surface geology.

Our knowledge of seismic wave generation by large explosions, particularly nuclear explosions, is very limited. Only three completely contained underground explosions with yields greater than one kiloton have been fired, all under very similar environmental conditions. The parameters that can significantly affect the magnitude and type of seismic effects produced by nuclear explosions should be experimentally explored so that theories can be developed which will permit reasonable confidence in our understanding of these parameters and deductions about them (7). The following parameters require study: (a) dependence of spectra of body and surface waves on yield of the explosion, (b) dependence of seismic wave excitation on the medium surrounding the shot, (c) effect of depth of burial, (d) effect of local environment, such as shot-cavity size and shape, etc., (e) effect of local geology and topography.

In many cases, but not all, it will be possible to investigate these matters through the use of high explosive rather than nuclear energy.

The following experimental nuclear shots should be carried out as soon as feasible: (a) a 5 KT shot in granite for information on the effect of shooting in another medium, (b) a shot in an environmental situation designed to decouple explosion-energy from seismic energy, (c) two 5 KT shots near the Rainier site but at appreciably greater depths. Theoretical studies which suggest the possibility of concealment by reduced coupling should also be experimentally tested as soon as feasible.

3. Propagation of Seismic Waves

Compressional, shear and surface waves are the principal types of seismic waves initiated by an earthquake or underground nuclear explosion. Compressional waves are transmitted most rapidly and follow ray paths through the earth's interior. The polarity of the initial motion in compressional waves was cited by the Geneva Conference of Experts as the main diagnostic feature for distinguishing earthquakes from explosions. Shear waves traverse similar paths at lower velocities. Shear waves may be resolved into transverse horizontal (SH) components and transverse vertical (SV) components. Surface waves are channeled in the wave guide formed by the earth's crust. They may be Rayleigh waves or Love waves. In the former, the vibration is restricted to the vertical plane of propagation; in the latter, the vibration is of the SH type.

An explosion in an homogeneous earth is a symmetrical source which initiates only compressional, SV and Rayleigh waves. An earthquake excites these waves together with SH and Love waves -- the exact partition of energy having an azimuthal dependence with the orientation of the fault, and the direction of faulting as parameters. In principle this difference between earthquake and explosion sources offers a possible method of identification (2, 5, 8). In practice the heterogeneity in the earth leads to mode conversion by which SH and Love waves are also initiated in explosions. Fortunately, the efficiency of mode conversion decreases with increasing wave length, as shown by observations that long period Love wave/Rayleigh wave amplitudes are larger for earthquakes than for explosions (5).

An earthquake relieves strain over a volume measured in cubic kilometers and behaves like an extended source. An explosion is essentially a point source. This essential difference may show up in differences in the spectra of seismic waves radiated from earthquakes and explosions (2, 5, 8). Similar effects may also result from the difference in the shallow depth of the explosions as compared with the greater depth of most earthquakes. Further investigations should be conducted for proper understanding and exploitation of such effects.

The problem of interpretation of seismograms is probably simplest for the case of long period surface waves, i.e., waves with periods of about 10 seconds and greater. Such waves are guided by the earth's crust and local irregularities are so small compared to a wave length as to have little effect. The duration of

the source will almost always be short in comparison with the period, consequently the source can always be treated as an impulse. There is every reason to suppose that these long period wave trains will have a sense (i.e., of direction), and that this sense will vary with azimuth from the source in much the same manner, although not in direct correspondence, as the P waves. Thus, explosions and anomalous earthquakes will initiate disturbances of the same sense in all directions, but most earthquakes will initiate disturbances having different senses in different sectors. Given a seismogram of a long period wave train then, we wish to determine a sense of motion at the origin, or, at least, a sense relative to that obtained from waves at other azimuths from the same source.

One approach to this problem which offers great promise is the so-called "black-box" approach (9). This method has the advantage that it does not rely on detailed knowledge of wave propagation in the earth and of the effect of the seismographs on the wave train. By cross-correlating, for many different lags, a standard output (one whose input was a single impulse of known sign) against output of current interest, and plotting the result against lag, a computational black box is obtained whose phase shift is equal and opposite to the black box under study. This means cross-correlating the record from a standard earthquake with the record from the shock being analysed to obtain a rough approximation of the seismic pulse shape in the vicinity of the source. Experience to date suggests that the match of distances and directions between standard and analyzed shocks need not be too precise. Analog networks and multipen recorders could be adopted in an extensive field program. Preliminary trials indicate that the sense of initial Rayleigh motion can be detected across the North American continent (3700- plus km) for at least some earthquakes of magnitude down to 4.5 and there is a good possibility that the method can be pushed to or below magnitude 4.0, which corresponds to about 1 or 2 KT. Additional work is recommended.

A second approach is the "phase compensation" method (5, 9, 9a) which attempts to synthesize source motion through the application of the proper Fourier transform. This method requires detailed knowledge of the propagation characteristics and of the instrumental response. Testing is only in the preliminary stage but there appears to be no major difficulties involved in obtaining this information with sufficient precision.

The problem of the structure of the earth's crust and upper mantle is of fundamental importance to seismology and is closely and inherently interrelated with

the problem of detection and identification of explosions and earthquakes. One well known method of exploring crustal structure uses the dispersion of long and intermediate period surface waves (5, 8). This method, particularly the group velocity approach, gives average structure over fairly large portions of the crust.

More detailed analysis of smaller regions may be obtained from seismic sounding with the shorter period waves generated by explosions (10). The outstanding work in this particular field has been done by the USSR, because of the large effort which has been made in comparison to that of the U.S. Sufficient talent and instrumentation are available in the U.S. to match and surpass this Soviet effort and at the same time to exploit a major tool for exploration of the solid earth. A program of crustal exploration based on explosion seismology, and including supplemental studies such as gravity traverses, etc., should be begun which draws on the skills, instrumentation and manpower of commercial geophysical exploration and which takes advantage of the experience and judgment of geophysicists specializing in the broader aspects of crustal structure. Such a program is certain to produce information on such basic questions as the modification of seismic waves by earth structure, the origin and manner of growth of continents, the mechanism of orogeny and isostatic compensation, and the composition of the crust and upper mantle.

Development of seismic instrumentation for use on the ocean bottom is discussed in a later section. Such instruments, strategically located in the deep oceans, may perform a valuable function in a detection and identification network and may also provide unique and important information on wave propagation (11). This could lead to understanding of the mechanism of generation and propagation of microseisms, the effect of continental boundaries on surface waves, the possible guiding effects of the sedimentary and crustal layers, propagation of low frequency underwater sound, and many others.

The series of test shots of both nuclear and chemical nature described earlier will contribute significantly to wave propagation studies as well as to the study of near-source phenomena (7). These shots should be highly instrumented and thoroughly exploited, partly because of the uniqueness of the source itself and also because of the precision with which the source may be located in space and time.

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In many problems involving elastic waves in layered media, wave length λ occurs in a dimensionless parameter H/λ, where H is the layer thickness. Models of elastic wave propagation in the earth may be constructed by greatly decreasing the layer thickness and increasing wave frequency in the same ratio. Thus, ultrasonic elastic waves in a 1 cm layer can correspond to seismic waves in the 35 km layer which forms the earth's crust. Ultrasonic models offer the possibility of duplicating conditions of seismic wave transmission in the earth as well as at the seismic source. Models of explosions and earthquakes should be studied to test proposals for discriminating between these sources. As an example, equalisation methods of operating on Rayleigh waves may be examined under controlled conditions when the polarity and shape of the impulse and the dispersion of the wave train are known beforehand.

The basic data of seismology are recordings of earthquakes and explosions as gathered by first class seismograph stations. Advances in research would accompany an increase in the number of such stations in the world and the most effective way to accomplish this is to upgrade existing stations (1). It is recommended that 100-200 of the existing stations in the world be equipped with modern instruments as soon as possible, without obligating the grantee beyond agreeing that the station would be maintained and operated at his expense. Existing traditions in seismology provide for access to records by qualified investigators. It seems desirable as a step in improving the US seismic capability to first equip existing American stations with the best instruments now available, and to establish new stations since the existing distribution is not optimum. It should be made clear that this action should in no way justify a decrease in the number of stations in a monitoring network.

4. Detection

The Panel recommends a broad program to find ways for improving the detectability of seismic waves from explosions and earthquakes. Such improvements will result in part from increased knowledge of the waves generated at the source and from more detailed knowledge of the influence on the propagation characteristics of the earth, as discussed in sections 2 and 3 above. In addition to these factors, however, improvements are certain to result from basic studies of the characteristics of microseismic noise, from the application of the most modern engineering techniques to the design of improved instruments and from experiments with novel detection methods. In the latter connexion, it may be pointed out that the recent development of ultra-long period seismographs has provided one of the most

powerful new means for detecting explosions, in spite of the facts that these instruments were developed for totally unrelated purposes and that earlier attempts to record explosions with the then-existing long period instruments were unproductive.

Before an adequate description of microseismic noise is possible, further information will have to be obtained in regard to its spectrum and its coherence from site to site as a function of frequency. It is also desirable to obtain information on the causes of variations of these properties, particularly the influence of storms and local winds, as well as the influence of the local geological structure. The Panel recommends a field programme for recording noise characteristics at frequencies between about 10 and 0.01 cps. Measurements should be taken over long enough intervals of time to show seasonal variations and should be taken at numerous locations to include sites with massive crystalline substructures, layered substructures and sedimentary substructures, both in coastal and inland locations. For this purpose, it will be necessary to equip teams with suitable broad band seismographs, perhaps recording the frequency ranges of 10 to 1 cps, 1.0 to 0.1 cps, and 0.1 to 0.01 cps. Data analysis will require the use of high-speed computers. There will be a need to develop agreed standards for describing noise properties, along the lines suggested in Appendix 12. Once satisfactory measurements of noise and signal characteristics are obtained, the specification of acceptable signal-to-noise ratios, acceptance bandwidths of seismographs and characteristics of filters and associated instrumentation should be possible.

A specific programme for the development of improved general purpose seismographs is recommended in Appendix 13. It may be noted that sufficient information now exists to commence with certain parts of this work particularly those parts which deal with the incorporation of advanced engineering concepts into the design of new equipment. Other parts of the work can be most profitably undertaken only after new information has been accumulated on properties of noise and signals.

Certain special purpose detectors are also recommended (3, 14). The development of unattended telemetering seismic detectors would permit the establishment of a network of auxiliary stations around selected primary stations. These proposed auxiliary units would be capable of receiving, storing and transmitting seismic data, either continuously, on an internally programmed basis, or upon demand by the primary

station. They should be sealed, tamper-proof devices, capable of operating for 30 to 60 days without servicing. All major functions of these units can be performed by equipment which can be assembled using components and circuits presently existing or in development. At the primary station, which would be manned, the data would be recorded and processed. Equipment to perform these latter functions should be developed on a parallel schedule with the unattended units. The main use of such stations would be to obtain more comprehensive information on the first-motion patterns of earthquakes. A second special purpose instrument is the "throw-away" or portable seismic detector (14). Such detectors, designed for rapid deployment in as many environmental situations as possible, could be used both for research purposes and by inspection groups for investigating unidentified events. They could provide comprehensive information on first-motion patterns as well as on the areal extent of occurrence and on the size of aftershocks. The instruments must be capable of continuous operation and transmission of data in analog form to a central recording station over periods of several days.

Of great importance in the detection and identification problems is the degree of signal enhancement that may be gained through instrumental and computational operations on the improved sampling of the seismic data made possible by the use of large arrays of seismometers (15). When the operations incorporate the elaborate complete signal enhancement techniques that can be performed on special-purpose digital data processing equipment, they may realize an improvement in signal-to-noise amplitude ratio in excess of $n^{\frac{1}{2}}$ where n is the number of seismometers in the array (16).

To realize the full benefit of arrays further investigations should be made into the use of communication theory as it has been applied to antennas and data sampling. Proper use of this study will require a knowledge of the signal and noise characteristics of the seismogram. On the basis of this knowledge, a theoretical study should be made of the optimum array patterns that could be used under the various environmental conditions encountered. In this study, attention should be given to obtaining a "universal" array, or at least obtaining maximum flexibility by switching and data processing. An investigation would be made into the influence of different geological, climatological, and seismological conditions on the responses of individual seismometers and of arrays of seismometers. On the basis of this study, selection would be made of the best array systems to be used under the several classes of environmental conditions.

These systems would be evaluated experimentally under the environmental conditions for which they were selected and mobile laboratories might be constructed for this work. By monitoring the responses of these systems, and by operating on the direct or recorded outputs with a computer the ability of the various systems to record natural earthquakes and possible explosion tests would be evaluated. The field tests would permit experimental determination of the influences of the station environment on the individual seismometer outputs and on the array capabilities. As a result of the field determinations, a selection of either a group of flexible systems or one universal system would be made (15).

The Panel places great emphasis on the immediate need to construct a complete experimental station incorporating all features of the seismic stations recommended by the Geneva Conference of Experts (17). Operating this station for a period of time would serve the two immediate objectives of providing experimental evidence on the capability of such stations to detect and identify earthquakes, and of assisting in working out installation and operational problems which would be encountered in establishing a control network. Subsequently, the station should be expanded to include facilities for testing other detection methods proposed by this Panel or methods which may be developed through future research programmes. A high priority should be given to testing arrays of up to 100 seismometers and testing a system of unmanned auxiliary stations. For maximum effectiveness, the station should be installed in a seismic region where the data collected would assist in more general research problems.

Finally, research should be stimulated to develop new methods of detection. The Panel suggests two specific approaches (18, 11). One method is based on a line of theoretical reasoning, supported by some experimental data, which suggests that seismographs installed and operated at depths of several thousand feet below the earth's surface may have the capability to detect smaller P-waves than those detectable at the surface. This approach is suggested by considerations which show that the surface noises, which now limit detection, may die off more rapidly with depth than do the signals of interest from explosions and earthquakes. A second approach, based on a somewhat similar line of reasoning, suggests that there may be extremely low noise levels at the bottoms of the oceans, at least at some frequencies. The development of a reliable operational detection system, based on either of these approaches, involves the solution of some major engineering problems; the expected signal-to-noise improvements, however, are potentially so great that the experiments

necessary to test the basic theories should be conducted as soon as possible. Work is in progress at the present time on the first method, and some preliminary equipment design work has been completed on the ocean-bottom seismometer.

5. Data Processing

One of the most significant new research tools which has become available to science in recent years is the high-speed computer. Because of the extremely high rate of information collection at seismographic stations, and because of the complexity of the mathematical problems whose solutions are necessary in understanding the meaning of seismograms, major advances could be made if such machines were to become more generally available to seismologists. At the present time, such machines are available only on a very limited basis. Yet, if the research necessary to solve the problem of identifying a high percentage of small seismic events is to be accomplished soon, and if the vast quantities of data which would result from a Geneva-type monitoring network are to be processed in a timely fashion, there is an immediate need for the services of a high-speed computer with the capability of the IBM 704 or 709 machines and competent operating personnel. The Panel recommends the establishment of a central computer facility, available to all seismologists, where the computations necessary to the research outlined in this report can be made (19). Allowance should be made for supplementary computing facilities which will also be required by individual research projects. A library of digitalised seismograms, to include earthquakes, explosions and noise samples should be maintained at the computing centre.

The computer centre might also undertake the initial development and evaluation of techniques for the continuous automatic processing of data from a Geneva-type monitoring system. The importance and magnitude of this task is evident when it is considered that a single station, as supplemented by certain possible equipment for improving the capability beyond that of the Geneva-type stations, might have an input data rate of as much as 2,000 samples per second. This data must be analysed, filtered, and combined in different ways to take full advantage of the array, and possibly of outlying remote seismometers, before it will be possible to make a decision as to whether any seismic event is a natural earthquake or whether it justifies further investigation. Since there are many thousands of events recorded per year at some seismic stations, to perform this analysis adequately by manual methods will require a large skilled staff. The use of computers should be investigated as a means of performing at an adequate rate the tasks of filtering and decision making that are required of the Geneva system.

As a result of research referenced in Sections 2, 3 and 4, new methods will emerge for analysing seismic data to infer properties of sources and characteristics of the earth. As soon as such methods show promise of assisting in the specialized problem of the Geneva monitoring system, or of assisting in general problems of seismology, they should be developed into practical operating techniques. Certain methods, such as the applications of equalization, machine filtering, etc., appear to be sufficiently well-developed so that work could commence in the near future on the design of operating units to perform the required specialized functions. These operating units could be field tested in the test station recommended in Section 4.

6. The New Level of Seismological Research: A Discussion of its Administration, its Budget and its Implications

A seismological research programme of the magnitude discussed in this report must draw upon the facilities of the universities, the government and industry for implementation. It is anticipated that many groups will submit proposals under the new programme of support. Some mechanism must be established for collating, evaluating and following the projects. It is recommended that an advisory panel be established, perhaps through the National Academy of Sciences, to perform these functions. The Panel has demonstrated how effectively a group drawn from research seismologists, physicists, mathematicians and engineers can function in advancing seismological research and it is recommended that the advisory panel be similarly constituted.

It is strongly recommended that this programme be viewed as a "package," one centrally funded and directed, in order to derive the fullest benefits.

In addition to projects definable as research, there is clearly a need to initiate immediately activity that may be described as "system development." Such activity would include planning in detail the complete world-wide seismic detection system. In its first phase of implementation, the system will probably resemble closely that envisaged in the Geneva proposal (since it will not likely be possible to develop anything more sophisticated in the time available). But planning must extend to later phases, in which improvements coming from results of research will be incorporated, because these improvements must be anticipated as much as possible to permit their orderly implementation into the then existing system.

"System development" will include development of new equipment, such as improved seismometers, and data processing and transmission apparatus, described earlier in this report. It will also include the field trials, mentioned earlier, of significant elements of the detection system as well as the planning of the operational procedures. As the system plan is established (and approved by the appropriate government agency), implementation must be programmed and executed with due consideration of funding limitations, manufacturing capabilities, logistical problems, and international agreements.

The Panel believes that the research programme can best be carried out by various existing private, university and government laboratories, co-ordinated by a panel of scientists, possibly under the aegis of the National Academy of Sciences. In contrast to this arrangement for research, the Panel recommends that the "system development" responsibility be assigned to a single well organized central laboratory. Such a laboratory should have competence not only in seismology, but also in development, engineering, and large system operation. The laboratory would likely sub-contract with private industry for much, or perhaps all, of the specific hardware development and procurement. However, it is essential that the laboratory have full responsibility for the planning of the system (including its orderly metamorphosis with time), for field trials, for implementation, and possibly for the American portion of its operation.

Tentative cost estimates are given below for the first two years of a programme which will continue thereafter at least at the levels indicated. The estimates are divided among three categories: (a) Research, (b) System Development, and (c) Nuclear and HE Detonations.

Individual Research Projects	1st year (thousands of dollars)	2nd year	
Equipping of selected stations with modern seismic equipment	$1,250	$1,000	
Study of shear waves	225	170	
Identification from aftershocks	100	100	
Long-period surface and body waves	1,000	1,000	
Geophysical investigation of crustal structure	1,000	4,000	
Equalization experiments	300	1,000	
Model studies	100	100	
Noise studies and development of standards	150	150	
Large arrays	500	1,000	
Deep hole detection	500	500	
Deep ocean seismograph	400	400	
Research computing facilities	750	750	
Library of digitized seismograms	50	100	
Theoretical studies of explosion sources	100	100	
Other	150	150	
	$6,575	$10,520	(sub-total)
System Development			
Unattended seismic stations	$ 750	$ 1,250	
Improved seismographs	300	300	
Portable or "throw-away" seismographs	200	230	
Automatic data processing	1,000	1,700	
System planning and field trials	2,000	4,000	
Implementation of detection system	(not estimated)		
	$4,250	$7,480	(sub-total)
Nuclear and HE detonations	12,000	12,000	
	$22,825	$30,000	(total, not including implementation)

The items in the research budget are not meant to be all-inclusive. Although they represent aspects of seismological research which are pertinent to the detection problem, each project can be justified on the basis of significance to fundamental seismological research. On the other hand, the appendices are not meant to define specific programmes in detail but rather to outline broadly needed research areas.

The Panel submits this programme of research as a means of realising the optimum contribution to seismology to the detection problem. In so doing it also recognises that this programme will result in dramatic advances in our knowledge of the earth's interior, of the mechanism of earthquakes, and of elastic wave propagation. Now that seismographic stations are being planned for placement on other planets, seismological research will bear on new questions relating to the origin of the solar system. Seismology is a fundamental tool, providing data to geologists, geochemists, geophysicists, astronomers, engineers, petroleum prospectors and underwater acousticians, etc., and rapid developments in these fields can be expected from this programme.

It is the opinion of the Panel that the research studies described in this document will certainly improve detection capabilities of underground nuclear detonations. However, the improvements are not likely to be evaluated adequately for proper assessment of value in a detection system before one year of research activity at best. Most of them will undoubtedly require more time, perhaps three years. Thus, it is important to conceive of the detection system as one which will gradually evolve with time and reach a high level of detection capability only after several years.

Appendix I

IMPROVED EQUIPMENT FOR EXISTING SEISMIC STATIONS

Frank Press and David T. Griggs

There are approximately 500 seismograph stations in the world. If many of these stations were equipped with modern time-keeping devices, three component short period seismographs (Benioff response or equivalent) and three component long period seismographs (Press-Ewing response or equivalent), much valuable data would accumulate. A particular use of these data would be in research programmes directed towards distinguishing earthquakes from explosions. For example, statistical studies could be prosecuted on the energy ratio of Love to Rayleigh waves, or the ratio of horizontal to vertical motion in L_g and R_g surface waves. Furthermore, advances in solid earth geophysics would be spectacular with so excellent a network of stations.

The Geneva conference of experts proposed that the existing network of stations be improved to provide adjunct service to the monitoring network. Since much importance is attached to improving methods of identification as soon as possible, it may well be desirable to implement this proposal immediately.

It is proposed that the 100 - 200 best stations in the world be equipped with modern instruments as soon as possible. This can be a unilateral action of the US or a joint action with the USSR. It should be made clear that this action would in no way justify a reduction in the number of monitoring stations. The instruments would be provided without obligating the grantee beyond agreeing that the station would be maintained and operated at grantee's expense. Existing traditions in seismology provide for access to records by qualified investigators.

It seems desirable as a step in improving the US seismic capability to first equip the American stations with the best instruments now available. Since the distribution of existing stations is not optimum, it may be necessary to establish new ones.

Equipment would be selected by a panel of American seismologists, perhaps appointed by the National Academy of Sciences. Administration and implementation might be under the aegis of an association of several universities with strong Seismology departments.

It is estimated that equipment and installation costs would amount to about 1-1/4 million dollars the first year and 1 million dollars in the second year.

The records from these stations covering the world will provide data essential to several of the projects discussed in the following Appendices. To ensure that these records are of high quality, it will be necessary to provide crews to assist in selection of the best sites in the vicinity of the station, in setting up and calibrating the instruments, and in instructing the station personnel in operation and maintenance. These crews should make periodic visits to each station for maintenance and to check on the performance.

Appendix 2

SHORT PERIOD SHEAR WAVES AND THEIR APPLICATION TO DISCRIMINATING BETWEEN EARTHQUAKES AND EXPLOSIONS

Carl Romney

1. Short period shear waves from the underground explosions Blanca (20 KT) and Logan (4.6 KT) were detectable to a distance of about 1500 kilometres, and thus, if suitable criteria can be developed, the shear waves may provide an important means for discrininating between earthquakes and explosions. However, a review of experimental and theoretical knowledge of short period shear waves does not suggest methods which can now be applied. It should be noted that little has been done in the way of detailed experimental studies of such possible methods.

2. Four of the more promising approaches to the problem were considered, as follows:

2.1 Existence of SH. In simple models which approximate the earth, theoretical analyses show that for explosion sources the shear waves will be polarized in the plane of propagation, while for faulting sources the shear waves will generally have components perpendicular to the plane of propagation. In such simple media the existence of shear waves with a transverse horizontal component (SH) would be an unambiguous indication of a non-explosive source. This theoretical result, unfortunately, does not apply to the real earth, where transverse horizontal components of motion are customarily recorded from explosions. Several mechanisms can be imagined which could cause such an effect, the simplest of which is the existence of geological discontinuities which are not strictly horizontal. Regardless of the mechanism, the result is that this particular criterion does not distinguish between earthquakes and explosions in the general case. Considering the heterogeneous nature of the earth's crust, it is unlikely that this criterion could become useful, except in very small areas of rather simple geological structure. The situation may be improved as regards long period shear waves, however.

2.2 Azimuthal Variations of SH/SV Ratio. In simple earth-models, theoretical considerations show that the ratio of SH/SV should be equal to zero in all azimuths from explosions. On the other hand, from faulting sources the ratio of SH/SV should vary with azimuth in a systematic way, depending on the orientation of the fault and the direction of the fault motion. In the real earth, SH/SV is not zero

from explosions as discussed above. A few observations from the Rainier explosion for example, showed ratios which varied from 0.9 at one station to 4 at another. The possible utility of the study of SH/SV as a means for distinguishing earthquakes thus depends on the ability of a given system of seismographic stations to discern the systematic variation with azimuth over and above the "noise" produced by variations in this ratio due to unknown causes along the different paths to the separate stations. This systematic variation should bear a relationship to the pattern of initial compressions and rarefactions in the P-waves, which should provide a test of the reality of any inferred SH/SV pattern.

2.3 Absence of Sn. The underground nuclear explosions in Nevada did not produce Sn waves. A similar absence has been reported from certain other, but not all, blasts. Sn is observed from many earthquakes.

2.4 Ratio of S/P. Since earthquakes are generally thought to originate from shearing sources, while an explosion is more nearly a pure compressional source, there is good reason to believe that the relative amplitudes of the shear and compressional waves might be different in the two cases. Discontinuities in the elastic properties of the crustal rocks will, of course, transform compressional waves into shear waves, and conversely. The ratios of S/P observed from underground nuclear explosions in Nevada were within the limits of normal ratios observed from earthquakes. However, it is not known whether explosions in other regions could produce waves which might be more distinctive.

3. In addition to these approaches, there are possibilities that the existence or size of the short period shear waves may be an indication of the depth of focus. This is based on Oliver's suggestion that the waves in question are high mode Love waves. If this is true, a source in the upper part of the crust should excite these waves, while a source deep in the crust may not.

4. It is recommended that an experimental programme be initiated to answer questions of the following type :

4.1 Can the ratio SH/SV be interpreted in terms of faulting sources? Is this interpretation consistent with solutions to the faulting from P-waves?

4.2 Can techniques be developed to determine direction of first motion in S?

4.3 Is Sn characteristically observed from earthquakes? Why is it missing from some blasts?

4.4 At what distances can S be detected, as a function of magnitude?

4.5 What is the ratio of S/P in earthquakes? In blasts? What are the variations in these ratios?

4.6 Can small variations in depth influence such ratios as S/P?

5. The required experimental programme would be conducted in two phases:

5.1 A detailed analysis of records acquired over the years at existing seismographic stations. Of particular interest would be the study of earthquakes from regions such as California and Japan where there are many stations with similar instruments.

5.2 The establishment of a unit consisting of about ten men and equipped with portable seismographic station equipment. This unit would operate in a selected area where there is a high probability of an earthquake occurring, and after sufficient data had accumulated, the unit would move to a new area. In each area, ten stations would be operated. Each station would have three component short period instruments (period about 1 second) as well as instruments for recording over a broad band extending from about 4 seconds to 0.1 second.

Costs and time schedules are estimated as follows:

Phase I	Study	1 year	$ 25 K
	Equipment procurement	1 year	200 K
Phase II	Operation of field stations	2 years	300 K
	Data analysis	--	50 K

Appendix 3

UNATTENDED AUXILIARY SEISMIC STATIONS

John Gerrard

1. Introduction

Preliminary results from the HARDTACK II series of underground explosions indicate that, within the network of manned stations specified at the Geneva Conference, methods must be found for ensuring a sufficient signal-to-noise ratio at the manned control posts, as well as means of obtaining comprehensive information on the first-motion patterns caused by an event. Simplified, unattended auxiliary seismic units can be used to advantage in achieving both these goals.

An array, employed for the purpose of signal enhancement, consists of receivers spaced according to such factors as the spectrum and coherence of the predominant noise at the site and the frequency and apparent velocity of the signal. Following a survey of background noise and the local velocity, theoretical methods can be used to determine appropriate data-processing techniques for the array. Use of unmanned seismic units as supplements to the control posts' attended equipment will improve the capability of the station to detect first-motion. In fact, consideration should be given to arranging small arrays of unmanned stations where this seems appropriate. This is especially important in normally seismic areas.

The incoming wave train that the seismic stations will be arrayed to receive will be that associated with the P wave. It is the direction of first-motion of this group that forms an important basis for identifying earthquakes. A plot showing directions of first-motion recorded from the same tectonic earthquake at different stations will usually exhibit zones or sectors of initial compression and dilitation separated by nodal lines. A similar plot for explosions should show compressions at all stations.

For plotting the first-motion, these units may be used to advantage in areas remote from the control station. This, of course, leads to more complete

coverage for the entire monitoring network. Signal-enhancement techniques may be applied to the unmanned stations similar to those devised for the manned stations.

This appendix contains a discussion of various aspects of the utility and design of unattended auxiliary seismic stations, to augment the Geneva network of manned stations. Storage and transmission of data from the auxiliary units is discussed. In particular, the discussion on telemetry is intended to indicate some of the capabilities of this form of communication. It is reasonable to assume that some of the auxiliary stations used to supplement a control-post array would communicate by land line though radio would probably be used for the more remote locations.

Environmental factors and countermeasures to detect interference are also discussed. A more detailed study of these could yield results which would have an important bearing on the reliability of the stations, particularly those in remote areas.

2. General Description of Auxiliary Units

The proposed auxiliary units would be capable of receiving, storing and transmitting seismic data, either continuously, on an internally programmed basis, or upon demand by the control station. They are to be vertical-component geophones capable of operating without attention. They are to be sealed, automatic devices containing a suitable seismometer, timing mechanism, transmitter, data-storage unit, and source of power. It is assumed that these units will be serviced at intervals of 30 to 60 days. It should be arranged that only the power and data-storage units be ordinarily accessible to the maintenance man and, in the event of equipment failure, various key components be replaceable as modules. This servicing will mainly comprise replacing or recharging the battery pack or power source and replacing the tape or permanent-record unit. The permanent storage will probably be a magnetic drum, tape, or wire. The storage mechanism will be designed as a sealed unit, capable of being installed and removed easily by the service man. The whole seismic installation will be made as tamper-proof as possible. In particular, the transmitted data will be coded to make the introduction of misleading data difficult.

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Telemetered alarm pulses can be initiated if any attempt is made to couple spurious signals into the antenna or tamper with the units. The data will be taken continuously and permanently recorded. Information may be obtained from the unit by interrogation from the central station, through a programmed schedule, or by continuous transmission. Methods of detection other than seismic may also be incorporated within the equipment. In order better to evaluate the reliability of the data, self-testing procedures may be incorporated, and results placed in storage, and transmitted together with environmental data such as temperature, humidity etc., if this is desirable. Time markers will also be placed in storage and telemetered along with the seismic data.

3. Seismic Equipment

3.1 Specification of Seismometer

Since the primary purpose of the auxiliary station will be that of detecting the first-motion of the P-wave pulse, the period of the seismometer used in these units will be relatively short. Further, due to the extensive coverage anticipated, many units will be in areas of strong motion for any event of interest. Consequently, it has been recommended that an instrument with overall features similar to the Benioff short-period vertical seismograph be used in this application. It will be assumed in this proposal that seismometers with similar response characteristics are suitable for incorporation in the unattended unit. Other requirements for the overall unit are resolution, ruggedness, stability, small size and weight, and the flexibility necessary for effective ground coupling under varied conditions. Temperature characteristics enabling the unit to operate under a wide range of environmental conditions are also essential.

Existing seismometers of conventional design should be evaluated as to their adaptability and suitability. However, if necessary, design and construction of a small seismometer of special type can be carried out. This has been done by the N.B.S. and the unit may be suitable for this application. A design feature that should not be overlooked is the incorporation of self-calibration or calibration measurement techniques into the station's capabilities.

3.2 Requirements imposed by Physical Environment

The most important environmental factor affecting receiver response is the "plant" of the unit. Unfortunately, even though great care is taken in choosing a site and installing the unit, inevitably there will be a number of them poorly placed. For many areas, the site location may be investigated by creating a signal artificially with a vibrator source and/or explosive charges, but this may not always be feasible. Also of importance in choosing the site would be noise conditions. The assignment of a weighting factor to each station, within limits of what is known about the site, would be useful. The factor assigned to each station would depend upon its environment and could be in the form of a number between 0 and 1 which could be used to weight the data from each station. Other factors that may affect the performance of the unit, such as temperature and humidity, will have to be taken into account if a complex piece of equipment is to be allowed to remain unattended for a period of 30 to 60 days. Safety features that permit rapid detection of tampering are important, as are features for calibrating the instrument automatically. Relevant data will be transmitted by telemetry.

4. Storage

4.1 Analog Versus Digital

One of the first considerations in the design of the storage and signal-handling equipment for the auxiliary seismic stations is the choice of analog or digital data-handling techniques.

There is much to recommend digital methods. In practice it is found that the necessary information may be extracted from data transmitted in digital form with a lower signal-to-noise ratio at the receiver than if it were in analog form. A reason for this is given below.

When converting an analog signal to digital form, it is necessary to decide upon the highest frequency to be analyzed. The choice of this frequency is based upon an estimate of the information desired and the range of frequencies in which this information is contained. Once this is done, a sampling interval is chosen so as to obtain adequate

reproduction up to the highest frequency. Usually the analog signal is prerun through an appropriate band-pass filter to eliminate the unwanted frequency components. In this case the seismometer itself may act as an adequate filter. If a comparison is made of the transmission properties of the filtered analog signal and its digital counterpart, both containing essentially the same amount of information, it is seen that a less complicated receiver is required to extract this information from the digital signal. The reason is that, in the digital series representing the information contained in one sample of the signal, only a decision as to the presence or absence of each digital pulse is necessary, whereas in the direct analog sample, an additional decision must be made as to the amplitude. In both cases the same total amount of noise is present. All of the corresponding error appears in the least significant figures of the number representing magnitude in the analog case. In the digital case, the same total uncertainty is more or less evenly distributed over all the digits in the group and, as a consequence, over all the significant figures of the number representing the amplitude. It is seen, therefore, that less error remains in the least significant figures in the latter case. Error in the other significant figures, which appear as gross fluctuations in the magnitude, may be eliminated. This elimination is possible through knowledge of the signal frequency spectrum and is accomplished as readily in the analog case as in the digital. However, as the above argument indicates, a greater proportion of the total error is subject to such elimination in the digital case. It follows then that digital reception allows a lower signal-to-noise ratio at the receiver for the same accuracy or for the same total information. Therefore, the effective receivable dynamic range of digital transmission is greater than for analog. Additionally, greater transmission range can be achieved with digital transmission for the same power and dynamic range.

Whatever the method of data handling used, it would be desirable that this method be used throughout the entire network. Therefore, considerations of data-processing methods to be used at the central

office would have a bearing on this problem. In this regard, the most important advantages of digital processing are flexibility and accuracy. For example, while it is possible to design analog equipment to solve a particular problem or perform a specific operation with the required degree of accuracy, any attempt to use the equipment on a slightly different problem often requires considerable modification of the equipment. On the other hand, with digital equipment it is generally only necessary to change the computer program.

Analog methods have advantages also, in that the output of transducers is in analog form and needs no conversion. Because of the fact that analog-to-digital conversion necessarily requires extra circuits and components, analog systems appear to offer a degree of reliability through simplicity even though they may not be as stable in operation. Since digital data is coded, important transmitted information may be lost as a consequence of losing one bit in the digital train. However, further coding of the digital signal can offset this disadvantage. Parity coding and redundant bits may be used to detect errors. Error correcting is also possible. By increasing the number of bits used to represent a character, codes can be made which are double error-correcting, triple error-correcting, etc. However, these are extreme cases and it is felt that a simple coding scheme together with knowledge of the signal spectrum would be sufficient for the purpose. Another method that may be used to increase the certainty of reception is to transmit the data twice, perhaps once backward and once forward. The discussion of data storage using magnetic tape, in the next section, implies that this would be quite feasible.

Although it has been stated that the seismometer output is in analog form, consideration should be given to the design of an instrument with direct digital output. The problem may be divided into two phases.

The first constitutes the design of a suitable sampling device. The object would be to have the output of the seismometer (voltage, current, light beam, etc) active only for short periods of time and at equal intervals. This could be accomplished in many ways. Examples

are: bistable electrical networks for electrical outputs; discrete light filtering, by means of spinning disks, for optical outputs; and for slow sampling rates, mechanical means, such as clock mechanisms, may be used.

The second phase involves finding a simple means of encoding the sampled data into digital form. In present analog-to-digital converters, this is done through the use of bistable electrical networks which are sequentially triggered. In searching for simple means of accomplishing this, several approaches are possible. One might involve a phenomenon that would have the inherent ability to subtract and leave a remainder. For example, if the coding is to be binary, and the sampled output is a voltage, this voltage must present itself in turn to a series of threshold voltages, each being half as large as its predecessor. For binary notation, a four-bit word could correspond to four threshold voltages, of 8, 4, 2 and 1 volts in succeeding order. If the sampling voltage were greater than 8 volts, upon presenting itself to the first threshold, 8 volts would be subtracted from it and the remainder presented to the second threshold, and so on down the line, until too little remained to trigger the last threshold. If at any point the remaining sample voltage is smaller than the threshold it faces, it moves on to the next one. Of course, the sampled output would not have to be a voltage, but the mechanism employed for digitization would possess this "subtraction" feature.

Another approach might be to allow the sampled quantities to operate a precoded device. Two currently used examples of this method employ the equivalent of a differential pulse-height analyzer and a cathode-ray tube. In the first case, the output of the analyzer is precoded, corresponding to various discrete values of the pulse sample. In the second, the electron beam is made to sweep horizontally across the tube face which is sensitized in a discrete pattern. The magnitude of the sampled analog signal determines the vertical position of the trace and its corresponding code representation. A third method would be to transform

the sampled quantities into a series of time intervals. This facilitates the use of counting techniques, the results of which are easily expressed in coded form.

Rapid progress is being made toward small, simple, and very reliable digital conversion systems, however, and it is anticipated that concentration of effort here could produce a suitable unit for installation in the auxiliary seismic stations.

4.2 Specification of Storage Unit

There are at least four alternatives from which to choose in deciding upon the best medium for data storage.

4.2.1 Magnetic Drums

The principal advantage of this type of storage method is its ability to furnish ready access to any portion of the memory. The method has draw-backs, however, one of which is the fact that a large amount of auxiliary equipment is required for its proper instrumentation. Further, its storage capacity is limited and it appears incapable of storing all the seismic data taken in a 30 to 60 day period without having unacceptably large dimensions.

4.2.2 Wire Recording

The use of wire has an important advantage in that a larger memory may be incorporated into a smaller package. However, there are transport problems involved in its use, principally at high speeds, which often result in breakage and snarling. A major engineering effort would be required to design the unit for reliable operation. It would, in fact, be necessary to utilize relativoly high transport speeds for the present problem since the ability to record information in wire is limited by its relatively poor frequency response.

4.2.3 Photographic Recording

Film offers interesting possibilities. It is possible to condense a great deal of information onto a very small piece of film. (The packing density can be made 100 times greater than for magnetic tape). This, of course, implies that a relatively small roll of film may be used for storage, and transported at very slow speeds. Records are also permanent and extremely difficult to alter when placed on film. Dry, automatic film-processing techniques are currently available and are probably adaptable to this purpose. There would be special problems in the design of photographic and electronic equipment used in connection with transferring the data to and from the film, but in general, the method appears feasible. An important unknown however, is the efficiency of dry film processing under various environmental conditions. In particular, it would be necessary to know its behavior in extremes of heat and cold.

4.2.4 Magnetic Tape

This material appears to be a suitable storage medium for application in unattended stations. Magnetic tape has a broad frequency response, is strong, and is capable of operating effectively over wide ranges of environmental conditions. Further, there is no problem in processing. Recording and playback instrumentation is highly advanced and needs no further development as would be the case for film. An example of a feasible tape-storage unit and an indication of its operation follows. In the example, the data is assumed to be in digital form; however, the general conclusions as to tape transport requirements would remain essentially the same for analog data. Consider a 10-cps signal, sampled 30 times per second. Further, consider that an 8-bit accuracy is assumed. This corresponds to a 7-bit amplitude ratio coverage of 127:1 in one direction, as

well as single-polarity bit. The digital sampling will therefore constitute one word every 1/30 sec. In transferring the data to tape there are several reasons why it is desirable to drive the tape as slowly as possible. The information should be packed together as tightly as possible to conserve tape, and also, high tape speed is desirable for convenient extraction of the data. The subsequent high readout rate resulting from high bit-packing densities leads to certain desirable telemetry features. (These are discussed in the next section). A packing density currently used is 500 bits per inch per channel. This may be increased, but it represents a reasonable current upper limit. On 1.25-inch tape, 18 channels may be used in parallel so as to increase the effective packing density to 1000 words or samples per inch of tape. Combining this with the previously indicated sampling rate of one sample per 1/30 sec., it is seen that for a standard reel of 3600 feet, over 17 days of continuous seismic data may be recorded, leaving two channels open for time marks and other information. By using thin tape, the same reel may be made to accommodate 4800 ft or more and larger reels could be used. In order faithfully to read out the information, it is advantageous to use a playback speed approximately 100 times the recording speed. Based upon the previous calculations, this represents a playback speed of 180 inches per minute. This is easily accomplished, and much greater speeds may be obtained.

One method of achieving rapid playback, and at the same time providing a temporary storage with easy access, is the use of two storage "bins". The tape is loosely piled in one "bin" after the playback heads. The other bin is before the playback heads. During readout the tape is fed rapidly from one bin to another by special capstans designed for the purpose. Neither tape reel need be accelerated, and the tape may easily be run backward and forward between bins in the event that it became necessary to repeat

the transmission of a given piece of data. In the meantime, the reels may be run continuously at a constant speed. The use of bins is limited, however, in that the tape is subject to snarling. An approximate upper limit to the amount of tape that can be kept in one bin is 200 ft. With the use of 1.25-inch tape and assuming the figures previously mentioned, the useful temporary storage capacity is equivalent to 2.4 million words or the amount of data ordinarily taken over a 20-hour period; so that readout must take place at intervals of less than 20 hours.

If recording at the station could be halted during periods of readout the same set of heads could be used for recording and playback. As readout would involve only one station at a time, this might be acceptable.

Of course it can be arranged that all the data accumulated by the station be played back and transmitted at one time. However, this would require a considerably more refined and powerful transport mechanism.

5. Interrogation and Telepetry

5. 1 Interrogation Interval

The information acquired by an auxiliary seismic station may be telemetered continuously or transmitted in a compressed state over short intervals of time. Reliability in communication is the principal factor in deciding between these alternatives. In this regard, high-speed readout appears to afford the best guarantee of reliable communication. The reason is, that in the event of poor and uncertain transmission conditions during the arrival of a suspicious signal, the stations should be able to transmit during momentarily clear conditions or to repeat the transmission. In this situation, maximum reliable data transmission in minimum time is essential. Its advantages lie in the fact that the monitoring network would be better able to act reliably and quickly upon receiving a suspicious signal, in spite of adverse conditions. It follows that transmitting intervals based upon a programming schedule set up

within the auxiliary station would be less desirable than an interrogation scheme controlled by a central office or manned station.

5.2 Number of Channels and Mode of Transmission

There are a number of telemetry bands from which to choose in selecting the best overall system. Final selection of the band or bands will probably depend upon international agreement. Factors to consider are telemetry range, maximum permissible transmitter power, size and type of antenna, crowded band conditions and reliability.

A few of the bands commonly used include: 215 to 245 mc, 160 to 172 mc, 140 to 150 mc, and the U.S. space telemetry frequency of 108 mc. With these bands, telemetry range is usually restricted to less than one hundred miles for a transmitter power of one watt. For powers of the order of 30 to 50 watts, a 500-mile ground-to-air range is thought to be feasible for FM transmission.

Digital data may be transmitted directly over a single FM channel. Considering, again, the output tape speed and corresponding amount of information readout per second by the auxiliary stations (as discussed in Paragraph 4.2), a single station would require a digital pulse repetition rate of approximately 25,000 bits per second. This requires a transmission bandwidth of about 500 kc. For a telemetry range of several hundred miles, approximately 25 watts of power would be required to ensure an adequate signal-to-noise ratio at the receiver. Any one of the standard telemetry bands may be used, providing there is sufficient channel space available. It is feasible to increase the transmitting range through the use of "constant altitude" balloons as relay stations. Such balloons are available and are capable of maintaining constant altitude with little drift for a minimum of 24 hours. The telemetry link visualized would be a seismic-station-to-balloon-to-central-office relay arrangement. With this scheme, overall ranges up to one thousand miles may be realized with a 25-watt power output at the unattended seismometer.

The relay apparatus in the balloon would require an omni-directional antenna, receiver and transmitter, and a relatively short-lived power pack. Each balloon could service a number of seismic stations. With this arrangement, each station, however, would have to have its own identification code as would each balloon. The fact that the balloons remain in position for only a short time is no problem. They can be released on a scheduled basis, a new one taking the place of the old at regular intervals.

Considering the fact that there will be a great many auxiliary stations in the field, the investigation of possible ways of reducing the complexity of the transmitted information is justified. It might be advantageous to restrict as many auxiliary stations as possible to transmission only of polarity information for signals of high frequency.

5.3 Specification of Telemetry Package

The transmitter may be transistorized with available components. The use of silicon transistors would permit operation over a wide temperature range (-50°C to + 100°C). The receiver may be designed to listen continuously with a very low power drain. The transmitter would be off until interrogated, whereupon it would operate for a short time at high power. The average power requirements would be relatively low. Extra channel bandwidth needed for high-speed transfer of information is proportional to the rate of transfer. Without this extra bandwidth, greater power would be needed.

6. Power Consumption

The different components within the auxiliary seismic package can be broken down as to their power ratings as follows:

The seismometer should require no power supply if a magnetic pickoff device is used. This can utilize a permanent magnet.

The analog-to-digital converter can be miniaturized and made to draw less than 10-15 watts for the relatively slow application contemplated.

A number of relays inevitably will be required to trigger the transmitter, initiate the high-speed tape transport and other automatic devices. These should require only a few tenths of a watt.

The radio receiver may be transistorized and operated at a level sufficient to initiate the various relays. This unit should not require more than about 0.5 watt.

The transmitter will also be transistorized and the power conversion should be relatively efficient. Since it will be running only about a tenth of the time, assuming a power efficiency of at least 50 percent, 25 watts transmitting power should require about 5 watts average power.

The tape-transport mechanism can be divided into two parts: that which runs the tape reels at a steady equivalent tape speed of about 2 inches per minute and that which drives the tape from one bin to another at a speed of 180 inches per minute or more. The steady-state slow-speed requirements should not exceed about 1 watt. Since only tape is being accelerated, the high-speed mechanism should require no more than 10 watts. Since the running time will be around 1/10 of the total time, the average drain for high-speed operation is approximately 1 watt.

The recording heads will probably require about 1/10 watt for transferring the data to tape. Certainly amplifiers and other electronic equipment will be used in connection with the tape storage. Estimated additional power requirement is 2 watts.

Total average power consumption of the unit comes to approximately 25 watts. An ordinary automobile battery can supply this power for approximately 24 hours under normal conditions. The newly developed nuclear power supply is reported to have an ampere-hour rating 200 times that of a car battery. At present, it is capable of delivering only five watts. If this could be increased, the device would be sufficient for the purpose.

If ordinary batteries were used, many means of supplementing and recharging them are available. A few examples are windmills, internal combustion engines, and solar batteries.

7. Conclusions

Design and construction of an auxiliary seismic station is feasible and there are apparently no insuperable problems. The development program as outlined in Section VII will provide the background experience and data necessary for establishing a realistic and reliable system of unmanned stations for the Geneva network. Operational experience will enable the optimum spacing of the stations to be selected consistent with the required identification level, the reliability of the stations and economical considerations. All major operations of the unattended units can be performed by equipment which can be assembled using existing components and circuits, with the exception of the miniaturized analog-to-digital converter. However, for the slow conversion rates in this application, no difficulties are foreseen in designing a satisfactory converter. Alternatives would be either to record and transmit the data directly in analog form, or to design and install a simple sampling device for storing and transmitting uncoded pulses. Either method is feasible and would involve somewhat less complicated equipment. However, data transmission and reception in these two forms is somewhat inferior to coded digital transmission and reception, and it is felt that, since the analog-to-digital converter will represent a relatively minor addition to the total equipment in the unit, no significant gain will be derived from either analog or uncoded transmission.

An important point, however, is the matter of slow or fast data readout. It is felt that very fast readout is highly desirable. To summarize:

Fast readout naturally lends itself to periodic interrogation of the unit. If a message is garbled, the tape can be rescanned rapidly and the data retransmitted in minimum time. Routine retransmission may even be considered as a means of reducing errors.

In the presence of adverse telemetry conditions, rapid data transmission is highly advantageous. This follows from the fact that during a time of

generally unsatisfactory reception, a momentarily clear channel can afford the means of communication.

Another reason results from storage-space limitation. With tape storage, recovery of the data depends upon the signal-to-noise ratio and the tape speed. The most efficient way to recover the data is to run the tape past the playback heads at high speed. Since the length of tape is limited, the packing density must be high if the required storage time is long.

The unit described should be designed for ease of modification and maintenance. It is felt that the state of the art will permit an adequate unit to be developed.

8. Technical Program

8.1 Phase 1 - Preliminary Experiments

8.1.1 A thorough study must be made of existing instrumentation and equipment which might be adapted for use in the unattended auxiliary seismic station. The design and operational characteristics of related types of equipment such as that used in remote weather stations should be investigated.

8.1.2 The feasibility of operating a remote seismograph can be demonstrated using existing equipment and techniques. It is recommended that several types of communication links be evaluated, along with both analog and digital methods of recording and transmitting the data. The trial system must be assembled using components which have low power requirements; however, power consumption is not the major concern during the initial tests. The prime concerns are reliability, fidelity of transmission, and the evaluation of data-storage techniques.

8.1.3 The tests must be set up under conditions similar to those that are expected to be encountered in the Geneva network. This implies a maximum distance between transmitter and receiver of

about 700 km. Operation of the trial system for about 90 days should give an evaluation of the anticipated reliability and should point up specific problems.

8.2 Phase 2 - Development and Construction of an Experimental Model

8.2.1 Based on the tests of Phase 1, an experimental model will be constructed. The objectives are: fidelity of transmission, reliability, adequate data storage, and low power consumption. It may be found advantageous to locate the seismometer in a shallow well several hundred feet from the building that houses the amplifier, power supply, data-storage unit, transmitter, and antenna. On the other hand, a single unit may be suitable.

8.2.2 An automatic calibration device must be provided and programmed so that the seismometer can be calibrated at intervals. The calibration information must be recorded and transmitted back to the manned control post.

8.2.3 Consideration must be given to cold weather operation, particularly in regard to the power source, antenna, and maintenance after heavy snow, or other adverse weather.

8.3 Phase 3 - Evaluation of Experimental Model

8.3.1 In order to test adequately the system it will be necessary to construct the receiving and recording elements of the reception equipment. Provision must be made for verifying multiple transmissions from each unmanned station and storing information from all stations in time synchronization.

8.3.2 Three experimental models will be required for laboratory and field tests, thus providing some comparative information and enabling interference tests to be made. For the first field test the three systems will be installed with their respective

seismometers on a common pier. The reception equipment should be located about 100 km from the transmission equipment. The systems will be operated with the masses of the seismometers blocked to check the noise level of the system, then with the masses unblocked to compare resolution, fidelity, dynamic range, and other features.

8.3.3 For the next test the unmanned stations will be located about 170 km apart and about 700 km from the receiving station in a seismic region such as California. Standard Benioff short-period seismometers recording on film will be placed at each transmission station as control instruments. Recordings will be made for a period of 6 months to evaluate reliability and fidelity of the system. Operational and instrumental problems that are noted will be evaluated so that they can be corrected when designing and constructing the prototype models.

8.4 Phase 4 - Construction of Prototypes

8.4.1 Based on previous tests, three prototype models will be built for further laboratory and field testing of the system. Environmental tests and simulated life tests will be conducted in the laboratory. Field tests will essentially duplicate the tests of the experimental models to be sure that problems uncovered during the operation of the experimental model have been corrected.

8.4.2 After field tests are completed, design changes will be made and the drawings brought up to date. The prototype model should then be representative of the number of field-test instruments that will follow.

8.5 Phase 5 - Data Analysis and Interpretation

8.5.1 Before large-scale field trials can be undertaken, it is necessary that adequate data analysis and interpretation equipment be made

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available. At present it is thought that digital analysis techniques should be used. Since the unmanned stations will be used primarily for identification rather than detection, the location information of the suspected event should be available at the manned control posts and can be used to program time delays into the data transmitted from each remote unmanned station. This will enable the digital computer to do cross-correlation, special filtering, and other operations on limited sections of the data where events are predicted to occur.

8.5.2 For the most part the data analysis equipment can be tested in the laboratory using stored information and test routines. Complete field testing will not be possible until a number of unmanned stations have been installed.

8.6 Phase 6 - Field Evaluation

8.6.1 Based on the results of the preceding phases, a number of unmanned stations can now be integrated into the experimental seismic station. About 100 unmanned stations should be used to give coverage completely around the manned control post to supplement the array and also have the outermost stations at a slightly larger radius than is predicted for the Geneva network.

8.6.2 Along with the selection of sites and the installation of the unmanned stations, the data-processing equipment will be installed in the manned control post. Field evaluations will start as soon as the first unmanned station is established and will expand as the remaining stations are installed.

9. Preliminary Estimate of Cost and Personnel

It is expected that the development and evaluation program can be completed 2 years from the date of initiation of the project.

FIRST YEAR

PHASE	MAN YEARS	COST ($ x 10^6)
1	10	0.2
2	20	0.4
3	10	0.4

SECOND YEAR

4	10	0.3
5*	10	0.2
6*	20	0.4
TOTALS	80	1.9

* It has been assumed that all equipment for the field evaluation of the unmanned stations (100) will be made available by the experimental station at no cost.

Appendix 4

AFTERSHOCKS AS A MEANS OF IDENTIFICATION OF EARTHQUAKES

Frank Press

We have examined the statistics of aftershocks with a view toward using their presence or absence as a means of identifying earthquakes. The study was limited to earthquakes of magnitude 4-5 and aftershocks which occurred within one week after initial tremor. The basic data were taken from the local bulletin of the Pasadena seismograph station. Earthquakes known to occur as aftershocks of an earlier large earthquake were eliminated. 122 earthquakes were studied of which 67 were followed by aftershocks within one week. There was no obvious relationship between number of aftershocks or the magnitude of the aftershocks and the magnitude of the initial shock.

The smallest aftershock had a magnitude of 2.3. The largest had a magnitude of 4.9. We have no data concerning the possibility of increasing the proportion of earthquakes with aftershocks by recording tremors of magnitude less than 2.3.

Without going into the details of possibility of spurious aftershock sequences and the use of special temporary seismograms at a suspicious epicenter, we conclude from these data that aftershocks are of some use in the identification problem. The capability of this method depends upon how quickly temporary stations can be installed near the epicentre of a suspicious event. For network density such as we have in southern California, the capability is of the order of 50%. It must be noted that with the southern California network there are a sufficient number of reporting stations to definitely locate the event as an aftershock.

Future research on this problem will involve study of a large number of earthquakes and aftershocks. Even more valuable will be a research program where temporary instruments are located at an epicenter and operated for some time. The temporary arrays of instruments would be moved from region to region to build up a body of data concerning earthquakes and aftershocks. As many as 10-100 detectors can be used in this moving array. Valuable data concerning the nature of the faulting mechanism would also be accumulated. It is possible that by seeking aftershocks below magnitudes of 2-1/2, the identification capability of the aftershock method may be increased beyond 50%.

Appendix 5

LONG PERIOD SURFACE AND BODY WAVES

Frank Press

1. Introduction

Very little is known about the initial spectrum of earthquakes and underground nuclear explosions. It is not unreasonable to expect, however, that earthquakes are more efficient in the generation of lower frequency body waves and suface waves than explosions of equivalent magnitude. This follows from the greater extent of the earthquake source and the finite velocity of propagation of the rupture of the fault. Differences in spectra of body waves and surface waves is therefore a possible method of distinguishing explosions from earthquakes. Preliminary studies on surface waves have revealed that this effect does occur (Press oral report to PSI, January 1959).

The faulting motion of an earthquake excites Rayleigh waves (motion confined to the vertical plane in the direction of propagation) and Love waves (motion in the horizontal plane perpendicular to the direction of propagation), the relative energy in each of these wave types being dependent on fault orientation, direction of slip and azimuth of detector from epicenter. An explosion in a homogeneous earth crust can only excite Rayleigh waves. The presence of transverse horizontal motion in seismograms from nuclear explosions implies that mode conversion occurs due to heterogeneity in the crust. However, it is reasonable to expect that the "scale length" of heterogeneity in the crust is small compared to surface wave length in the range 30-200 km. For these long period waves mode conversion would be less effective and long period Rayleigh waves would be more efficiently excited compared to Love waves than is the case for earthquakes. This suggests another method for separating earthquakes from nuclear explosion, one involving the relative energy distribution between Love waves and Rayleigh waves. Oliver (oral report PSI, January 1959) had conducted preliminary studies. Most earthquakes appear to have significant "strike slip" components in the motion at the fault, which effect is conducive to Love wave generation. However, the statistics of strike slip versus dip slip earthquakes must be determined before the ultimate capability of the method is known.

Surface wave methods of identification offer the advantage that they are free from shadow zone effects. Furthermore, the efficiency of surface wave propagation is such as to permit all stations within about 3000-4000 km from the source to contribute data for yields equivalent to magnitude 4.4 or larger.

For reasons given above long period body waves may also be useful, primarily by spectra comparison and by the ratio SH/SV.

The construction of inverse transfer functions for surface waves to remove amplitude and phase distortion due to wave-guide propagation should yield impulse forms which would be useful for identification. In principle, explosions would show cylindrical symmetry with respect to the epicenter; earthquakes would not.

2. Research

To fully assess the capability of the above methods requires an extensive research program. Particular emphasis would be on statistical studies of spectra, Love/Rayleigh energy distribution, SV/SH ratios of earthquakes, quarry blasts and underground nuclear explosions. Also phase and group velocities of surface waves and their variations across continents would be studied with special tripartite arrays of long period seismographs. Data from Logan and Blanca as recorded at Pasadena, Palisades, Berkeley and St. Louis are useful, but more explosion recordings of surface waves are needed. Several groups are capable of carrying out this work including those at Caltech's Seismological Laboratory and Columbia's Lamont Observatory.

3. Instrumentation

It is important that a three-component long period seismograph system be adopted as soon as possible in order to insure that a wide distribution of a standardized instrument be made early enough to exploit any future underground nuclear tests, and to expedite the gathering of earthquake statistics. What is needed is an instrument which discriminates against 6 second microseisms yet offers magnification in excess of 20,000 for periods between 15 and 30 seconds. The seismometers are now available (e.g. Lehner and Griffith, Pasadena). Photographic or direct recording together with digitalized output (2 samples/sec) is required. Computing machine facilities are needed to extract from the digital data the following:

3.1 Spectrum of P. SV, SH, LQ (Love), LR (Rayleigh) and entire seismogram.

3.2 Ratio of SV/SH (in time and frequency domain).

3.3 Energy in LQ and LR trains; energy density, as function of time and frequency.

3.4 Phase and group velocities of surface waves.

3.5 Program for use of inverse transfer function to obtain initial impulse shape for LQ and LR.

Dr. Benioff suggests an approach to the instrumentation problem in his report.

It is recommended that a vigorous research program be established along the lines outlined above, one involving instrument development, installation and operation of long period seismograph tripartite arrays, computer programming, data analysis, theoretical studies of surface wave generation and propagation (including the inverse transfer function problem). Work on existing seismograms can yield some useful data but significant progress must await implementation of the more ambitious program.

Appendix 6

DEDUCTIVE SEISMOLOGY

Leon Knopoff

Observational seismology is concerned with the inductive problem, which seeks the solution to the question, "Given a set of observations, is it possible to make an inference as to the conditions within the earth and at the source that may have given rise to the observations?" A solution to the inductive problem if it can be obtained, is usually not unique and therefore should be evaluated in terms of some probability or other weighting factor which describes the likelihood of the solution being correct.

On the other hand the deductive problem is exact. Given a model of the earth, we ask, "Is it possible to construct the seismogram that would be obtained were the model Earth excited in exactly the way we specify by the model source and recorded by the model seismograph?" This is of course a problem in mathematical analysis.

The first assumption that we shall make is that we are dealing with problems in linear mechanics so that linear transform procedures are permissible. This is of course an unwarranted assumption for the regions of excessive strain near sources of large energy release, but we shall adopt a definition of source, in these cases, which will include all the regions of space which do not have a linear behaviour.

If the problem to be solved is appropriately described, then a specification of the nature of the structure, the source and the receiver must be made. The source is specified according to some enlarged definition as above. We solve problems in the realm of linear theory.

The problems of linear wave motions in solids can be divided into two groups: those of geometrical theory which determine the arrival times of the various events and those of physical theory which determine the character of the wave motions following the arrivals. The terms "geometrical" and "physical" are chosen by analogy with optics. Geometrical seismology is the usual travel-time seismology and thus is taken to be a solved problem in view of the foundation of this type of work upon Fermat's principle. Physical seismology is concerned with the nature of the wiggles immediately following the onsets of events. By analogy with optics, physical seismology is concerned with such problems as diffraction, scattering, interference, absorption, anisotropy, etc. in seismology. In principle, these

problems are solved by obtaining the solution to a certain boundary value problem. We concern ourselves with the problems of physical seismology since the deductive problems of geometrical seismology are trivial (although the inductive problems of geometrical seismology are not).

The seismographic interpretation problem will in general suggest a number of appropriate problems for theoretical analysis. The theoretician will, if possible, obtain a solution to these and compile a catalogue of solutions for a number of hypothetical structures, sources and receivers. The interpreter will then scan the catalogue in the hope that some similarity with a theoretical solution will permit the identification of the structure, source and receiver. Similarities in parts of the records will suggest refinements in the structures to be calculated by the analyst; these in turn should yield solutions which should improve the fit.

The difficulty with the deductive method is that solutions can be obtained only for those systems which can be described in mathematical terms. The real Earth will always be more complicated than one can mathematically describe. A corollary to results obtained from elementary structures is that the more complicated the hypothetical Earth structure considered, the more complicated will be the resulting theoretical seismogram.

In recent years, it has become apparent that we can treat theoretical problems in seismology of almost any degree of complexity with certain approximations. The only restrictions on this statement are those of 1) the size of the computational equipment available that is capable of handling the problems corresponding to complex structures and 2) the validity of the solutions in view of the approximations which may have been made. In other words, if we are given a structure, a source, and a receiver, a solution to the elastodynamic wave propagation problem can be obtained although this may only be approximate and perhaps may be too cumbersome for numerical evaluation unless computers of sufficient capacity are available.

To fix ideas, we shall assume that the properties of the source and receiver are given and therefore the problem of deduction is reduced to the determination of the influence of a given structure upon the wave propagation from certain idealized sources and as observed by certain idealized receivers. It will be assumed the reconstruction of the seismogram is possible from this solution for the case of an actual source time function by taking a convolution of the response to the idealized

time dependent source with the actual source function. Similarly it will be assumed that it is possible to obtain the response of a seismograph with given filter characteristics (frequency response) by again taking a convolution with the response to the "flat" receiver of the integral.

It is now apparent that two types of solutions may be considered. These two solutions correspond to 1) sources excited as impulses in the time domain and 2) as impulses in a time-transform domain. We may take (or obtain) any linear time transform of a time dependent solution and have a representation of the solution. We shall henceforth use frequency as the transform variable but this could be understood to be only one representation of the general Mellin transform problem. Solutions for certain structures have not always been obtained for delta function time sources; however, solutions in these cases have been obtained for the delta function frequency source. In some instances solutions have been obtained for both kinds of sources. This suggests that the two corresponding representations of the motion observed at the seismograph station be available for direct comparison with the theoretical solution. These are 1) the direct seismographic record of the motion as a function of time and 2) the Fourier (Mellin) transform of the seismic record; the appropriate representation of the observational record is then chosen to correspond to the form in which the theoretical solution is given. This procedure is suggested, rather than that of inverting the theoretical Fourier transform into the time domain in those cases where this form of the theoretical solution has been obtained, because 1) this inversion may not be elementary and 2) because the combination of the response with the filter characteristics of the receiver is very easy in the transform domain.

Before describing the problems which have been solved and the prospects for solving others of similar but perhaps more complex structure, we first consider the eigenvalue problems of guided wave propagation. With the use of large computers, the eigenvalue problems can be solved as accurately as the size of the computer will allow for <u>any</u> given structure. The solution to the eigenvalue problem has a two-fold worth. First, guided wave solutions have been used directly to determine structures in the inductive problem by comparing phase or group velocities between the theoretical results and observations of these velocities in extended oscillatory wave trains. Second, in the problems of impulsive wave propagation through these same structures,

the location of the eigenvalues in the complex frequency domain is most valuable in some techniques of the evaluation of the wave motion.

Some boundary value problems for either of the two kinds of source functions have been solved exactly. The number of these exact solutions is small. These solutions include 1) solutions for point sources in infinite, isotropic, homogeneous, elastic media, 2) half-space problems, 3) diffraction by a rigid and by a perfectly weak half-plane, 4) problems of media having a small number of parallel layers, 5) the scattering of waves from point sources by imbedded single elastic spheres and cylinders in infinite elastic media, etc. Convolutions of these results for distributed sources in space are considered elementary.

The exact solutions are not always easily evaluated in either the time or the frequency domains. Hence recourse to some type of approximation is indicated. The approximations considered here are of three types: the low frequency approximation, the high frequency approximation, and the approximation of boundary conditions.

The low frequency approximation in single scattering problems is easy to obtain and is usually a simple function for simple geometries of scattering centers. If multiple scattering can be neglected, then both the Fourier transform and its time inversion for the two kinds of sources are elementary functions in the low frequency approximation and the effect of local inhomogeneities can thus be determined for a seismogram. We assume the location of all inhomogeneities to be known. The long period motions at great distances are also easy to obtain for simple structures. One advantage of the long period approximation for the analysis of earth structures at very great distances is that most earth structures can be considered as being of a much more elementary form than in the same approximation at short range.

The high frequency approximation is much more complicated as an analytic problem. Because wave functions are usually very oscillatory with frequency at high frequencies, the delta function time source is the one most valuable. The high frequency approximation corresponds to the initial motion of the seismogram following each arrival. The high frequency solution has been obtained. The advantages of the high frequency approximation are that a superposition of solutions is possible, the superposition corresponding to a superposition of structure features. In a complex situation, the solution is obtained by constructing all the possible ray (arrival)

paths and constructing the wave motion following these events by considering the geometrical diffraction effects of all the obstacles corresponding to the alteration of the path of travel of the event, each obstacle considered separately as a diffracting system. The convolution of this result with pulses whose duration is non-zero but short compared with the travel time is simple; complex seismograms have been constructed from some structures of intermediate complexity (small numbers of diffracting surfaces). These show many of the seismographic characteristics found in observational data.

Superposition in the low frequency approximation may not be possible since superposition corresponds to the distortion of incident wave fields by multiple scattering. Here we consider wave lengths much larger than obstacle dimensions. Again, superposition of solutions for individual elementary structures may not be possible for a complex structure made up of several elementary structures because of numerical difficulties in evaluating the fields. In these cases, if an intelligent guess can be made as to the nature of the fields at the diffracting surfaces, then an approximate solution can also be obtained. This technique of approximating the boundary values of the fields is called a "saltus" technique. A number of geometrical configurations have been solved by this method to obtain approximate solutions. In those cases where exact solutions also exist for the same geometries, comparison has been made between the two solutions and the quality of the guess evaluated. It has been shown that most guesses are not too unsatisfactory if some measure of physical insight is built into the guess - that is to say we do not make the guess blindly. The saltus problem is an exact solution in itself and cannot be used in an iterative procedure to improve the solution since the solution is obtained for specified, although unreal, boundary conditions. It is the solution to some problem although one not necessarily connected with the boundary value problem given at the outset.

Solutions have been obtained for all the elementary geometries by one or more of the above methods, the elementary geometries are half-spaces, layered media, wedges, half-plane diffraction problems, imbedded spheres, imbedded circular cylinders, imbedded wedges, imbedded cylinders of irregular shape, the influence of irregularities in smooth simple surfaces, etc. The construction of the seismogram for more complex geometries is an exercise, although an approximation in the usual case, an exercise which may require extensive data processing and computational and data handling facilities of some size.

In addition to the above techniques for obtaining solutions of problems involving homogeneous media, procedures have been developed for the treatment of inhomogeneous media (velocity gradients) and absorptive media and for determining the influence of such media upon wave shape. In the cases of absorptive media, the solutions for nonabsorptive media need only be modified by a simple transfer function. The inhomogeneous media have solutions both in the long and the short wave length limits.

The problems which have not yet been treated but are now undergoing study with a considerable degree of effort include 1) an evaluation of the influence of anisotropy upon wave shape and 2) improvements in the techniques of superposition of solutions for elementary structures to construct seismograms for structures composed of these elementary elements, 3) improvements of approximation techniques and 4) obtaining exact solutions where only approximate solutions now exist.

In summary we can say that, to a greater or lesser degree, a theoretical seismogram can be constructed for any given structure. The limitations upon the solution are 1) the quality of the approximations used in the solution and 2) the size of available computational facilities for plotting numerical values of the solution. The demands upon the computational facilities increase as the hypothetical structure becomes more complicated. In recent years, we have progressed from a state of awe at the magnitude of the calculation involved in problems of elastodynamic wave propagation and a state of apprehension whether a solution can be obtained to a state of confidence that the construction (not the reconstruction) of seismograms of severe complexity is indeed possible even for problems of elastodynamic wave propagation in complex, but describable structures.

A comprehensive theoretical program in deductive seismology could be carried out with a modest budget - exclusive of funds for the necessary computation, which are treated in the appendix on Research Computers. It is believed desirable that two or more more institutions participate in this effort. The budget required is estimated as $ 150,000 per year, exclusive of computer time. This level of support would, in two or three years, result in the ability to predict the transmission characteristics of structures of considerable complexity - perhaps approaching those found in nature.

Appendix 7

NEED FOR HIGH EXPLOSIVE AND NUCLEAR TESTS FOR RESEARCH PROGRAM

Kenneth Street

1. Introduction

The problem of seismic identification of a nuclear explosion is ideally solved by finding some readily detectable, characteristic, seismic phenomena associated with an explosion (and which persists when the explosion is carried out under any practically realizable conditions) and not shared by any natural event. To date no such phenomena have been found and all proposed schemes (i.e., first motion, long waves, etc.) involve identifying some seismic events as definitely natural earthquakes, leaving as unidentified a class consisting of explosions and the rest of the natural events. The events in this latter class then have to be further identified by other than seismic means (i.e., inspection) and the aim is to make this class as small as possible.

It is imperative that the parameters that can conceivably affect to a significant extent the magnitude and type of seismic effects produced by a nuclear explosion be explored in a thorough manner. This is necessary so that these effects can be reliably compared with those produced by natural earthquakes. Thus any differences that are to be used for discrimination should be shown to be valid under all significant conditions. Undoubtedly the most fruitful approach in the long run will be the development and testing of a sufficiently detailed theory to permit reasonable confidence in our understanding of the important parameters and deductions about them. However because of the complicated nature of the phenomena involved and the urgency of getting some of the most important questions answered in as short a time as possible, a concurrent semi-empirical approach is also needed. Both of these approaches require explosive testing.

In the following sections of this appendix, the parameters needing study are outlined and some typical experiments for this purpose are indicated. At least the first three kinds of experiments listed in Section IV should be undertaken as soon as possible since the results might make a large change in the evaluation of the capability of a seismic identification system. It is estimated that a reasonable experimental shot program can be carried out for an annual expenditure

(continued for at least two years) of ten million dollars for placing and firing shots and two million dollars for seismic instrumentation. It is imperative that these experimental shots be properly instrumented.

2. Parameters Requiring Study

It should be emphasized that all of the underground nuclear explosions carried out to date by the U.S. have been fired under very similar and quite special conditions. They were all near-surface (less than 1000 feet depth) explosions in water-saturated Oaksprings Tuff of a single mesa at NTS. Thus the experimental data at the present time are restricted to a very small sample of possible shot conditions.

In order to describe the seismic effects of a nuclear explosion sufficiently well so that these can be confidently compared with natural earthquakes, it is necessary to investigate (either theoretically or experimentally) the effects of the following parameters on those body and surface waves proposed for use in discrimination:

2.1. Dependence on Yield. It is necessary to know the dependence of the various body and surface waves on the yield of the explosion. This together with the attenuation of the wave with distance determine the size of the "signal" one has to work with in any attempt at identification. Tamalpais, Rainier, Logan, and Blanca (Evans will be dealt with separately) gave some experimental data for yields from 60 tons to 20 KT fired in NTS Tuff. The uncertainties in the yield-amplitude relation are still quite large and additional data would be very useful.

2.2. Medium. All underground nuclear shots to date have been fired in NTS Tuff. It is very desirable to determine the effect on the pertinent seismic waves of shooting in different media - i.e., granite where the sound speed (20,000 ft./sec.) and crushing strength (30,000 psi static) are quite different from Tuff (8,000 ft./sec. and 8,000 psi).

2.3. Depth of Burial. Underground nuclear shots to date have all been fired at depths less than 1000 feet and in the side of a mesa extending about 2000 feet above the surrounding country. Data should be obtained at much greater depths - e.g., 10,000 feet.

2.4. Local Environment. The environments close to the explosions in the Rainier and the Hardtack underground shots were all determined by the exigencies of weapons testing and not their possible effect on distant seismic waves.

Thus all of these shots were fired in modest sized rooms connected to tunnels and stemmed with sandbags down the tunnel. It is necessary to determine if it is possible to construct a local environment which will reduce or change in type the distant seismic effects associated with a given yield.

2.5. Large-scale Environment (Geology). The available data on nuclear shots are from a single geological environment, namely the side of one mesa at NTS. The fact that Love waves were unexpectedly produced by the explosions suggests that the environment within a wave length or so may play a considerable role in determining the distant seismic effects.

3. Use of HE to Mock-up Nuclear Explosions

While nuclear explosions have some characteristics (high concentration of energy, high temperature and rapid rate of energy generation) which are quite unique and cannot be mocked-up with HE, it is quite likely that in a large number of situations the distant seismic effects will be very similar. Thus it should be possible to use HE in studying such parameters as depth of burial, effect of geology, etc., which should not depend on the unique features of nuclear explosives.

The advantages of nuclear explosives are their small size, which makes emplacement easier under some circumstances, and their relatively small cost for the larger explosions. At the 5 KT level, TNT is about ten times as expensive as nuclear explosives and at the 1 KT level about twice as expensive. Against this must be balanced the problems of radioactivity and politics. Since it will probably be difficult and inconvenient to use nuclear explosives under some of the conditions otherwise desired, it is very important to verify that HE can be used, at least under some conditions, to mock-up nuclear explosions.

4. Decoupling

The question of whether conditions can be found (or made) in which the distant seismic effects depended on for identification can be greatly reduced or changed in character is a very important one. If this is possible, the effective yield threshold of a seismic net may be greatly increased or an explosion may be mistakenly classified as an earthquake. On the basis of theoretical work methods have been suggested which could lead to a large decrease (factor of more than 10 or so) in the amplitude of waves generated by a given yield.

That there are conditions under which the coupling can be very small is demonstrated by the Evans shot. Evans was fired in a room approximately 15 feet on a side, located at the end of a tunnel and at a depth of 830 feet - conditions very similar to the other underground shots. The yield measured radiochemically was about 50 tons. Yet based on the seismic yield-amplitude curve from the other underground shots, one would say that the yield was less than 10 tons. It is not known why Evans failed to couple seismically but a vigorous attempt should be made to try to understand and to reproduce this unexpected behavior.

5. Experimental Program

An experimental program for the use of nuclear and HE explosions to explore a number of the parameters possibly affecting the seismic signals needed for discrimination between explosions and earthquakes is outlined below. It is assumed that if these events are carried out they would be properly instrumented with seismographs, both those specified by the experts at Geneva and any others that might prove advantageous.

The first four experiments discussed below are those that it is felt should be carried out as soon as possible because the results might make a large change in the evaluation of the capability of a seismic system. The feasibility of doing all of these experiments has not been examined in detail; some are obviously quite feasible, others appear to be so after a cursory examination, and some will have to be looked at in much greater detail to decide.

5.1. An approximately 5 KT nuclear explosion should be carried out in granite. This will give information on the effect of another medium. In order to do this shot expeditiously, it should be done at NTS if the granitic structure there proves to be suitable.

Rough cost-and-time estimates have been made assuming a 5 KT shot at 770 feet located in the northern part of NTS. It appears that all construction can be completed in five months after authorization. Assuming one month of user occupancy this gives six months over-all. It is estimated that this shot (not including off-site measurements) will cost about $1,500,000.

5.2. A decoupling shot should be fired to determine if such local environmental factors as those proposed on theoretical grounds can greatly diminish the

distant seismic waves. Such a shot at a yield of 1.7 KT might require six months to one year and cost 2 to 3 million dollars - assuming a suitable site (near water, etc.) can be found.

5.3. Two approximately 5 KT nuclear shots should be fired near the Rainier site but at greater depths in order to study this effect. A shot in Tuff just above the dolomite (2,000 to 3,000 feet) would be useful and quite easy. The second shot should be at a depth of about 10,000 feet. This is considerably more difficult and would probably require about two years for preparation. It is estimated that the cost of the cased hole alone would be about $3,000,000.

5.4. An HE shot of 1 kiloton equivalent should be fired near the Rainier site. This would give a direct comparison of the effects of HE and nuclear shots of comparable size and in the same environment. A preliminary estimate indicates that a shot such as this could be done for about $750,000.

5.5. Large shots (100 tons to 1 KT) should be fired at a continental margin. This would permit:

5.5.1. Investigation of seismic wave transmission in a region which our present experience suggests is poor in this respect, possibly because of the thick sediments.

5.5.2. Investigation of the asymmetry of the radiation pattern when the source is near a large crustal discontinuity.

5.5.3. Study of underwater sound generated by a source in shallow water or underground near the continental margin.

5.5.4. Determination of travel time curves and structure of the crust and upper mantle for oceanic and continental paths.

5.5.5. Investigation of geologic structure where present knowledge is weak but of great importance. For this purpose two large shots in about 50 fathoms of water, one off Montauk Point and one off Cape May on the east coast, would be one possibility. Another good site would be off the Gulf coast.

5.5.6. A shot located out of the complex structure of the western United States. Such a shot would permit the effect of this structure to be isolated when the data are compared with previous data.

5.5.7. A shot in the hard granitic rock of the Canadian Shield. Recordings of this shot made on the Canadian Shield would be relatively free from the effects of the near-surface heterogeneities. This shot might be the same as 6.

5.5.8. Two additional scaling shots should be fired at the Rainier site. One at about 1/4 KT and one at about 1 KT. These will better define the yield amplitude relation in the low yield range.

5.5.9. Use should be made of explosions carried out for other purposes. Thus surface waves should be recorded (long period 15-sec. instruments) on quarry blasts in the 20,000 to one-half million pound region. Nuclear shots such as the proposed 10 KT Gnome shot of the Plowshare project should be well instrumented. This shot in a salt bed in New Mexico should give very valuable data.

In addition, a program should be immediately initiated to detonate many small (10 - 1000 lbs) high explosive charges in all kinds of natural media to determine the nature of the explosion pulse and the characteristics of its propagation in homogeneous media. A correlative program of seismic theory and model studies should be pursued to the extent that it is feasible, to determine more exactly the probable nature and radiation pattern of earthquakes.

Appendix 8

SEISMIC WAVES IN THE INTERMEDIATE PERIOD RANGE

Jack Oliver

1. The waves discussed here may have periods of from 1-20 or more seconds but generally fall in the range 4-12 seconds.

1.1. Body Waves.

Ordinary long period seismographs frequently record body waves in this period range from earthquake sources. Most studies of these waves are based on the travel times of the various phases, with, if anything, only a qualitative discussion of the frequency content. Few quantitative spectral studies have been attempted, partly because of the poor quality and great variability of instrumentation throughout most of the world. At the Geneva conference last summer, the U.S.S.R. presented evidence based on more sophisticated studies of body wave frequency content and several articles in the recent literature suggest that they are investigating this problem vigorously. Such studies are becoming feasible for them because they have in the U.S.S.R. and Red China a large network of stations with fairly uniform instrumentation. From studies of this kind one might hope to learn more about attenuation of waves within the earth, focusing (possibly frequency dependent) as a result of structures within the interior, details of the source, etc. A better approach to the energy content of seismic disturbances and an improved magnitude scale should also follow. Since seismic waves are likely to be our best source of knowledge of the earth's deep interior for some time, developments of this kind are essential. Furthermore, no breakthroughs in instrumental development are required. Only the application of instrumental and computing techniques already in existence in other fields is needed.

1.2. Surface Waves.

For paths which are entirely continental, surface waves in the intermediate period range propagate more efficiently to great distances than other phases. For example, the Palisades station on the east coast of the United States records only surface waves from small shocks in California. These surface waves fall in the

intermediate period range. The waves of largest amplitude are associated with group velocity extrema of dispersion curves for waves of the Love and Rayleigh types.

Waves of this period predominate partly because of favorable dispersion characteristics, partly because seismograph response and excitation by the source are both unfavorable to waves of greater length, and partly because waves of shorter length are affected more adversely by the irregular near-surface media.

We have just recently begun to understand the mechanism by which these waves propagate. We are in the position to learn much more, but, in many cases, lack the necessary data because of poor instrumentation. Phase velocity information would add much to this kind of study. Since there is some reason to believe that the high frequency (1 second) surface waves recorded by short period instruments may be interpreted as higher mode propagation in the surface wave guide, it is important that these waves be studied in conjunction with the intermediate period waves.

When the path is oceanic we frequently record wave trains with periods of 5-15 seconds which are not well explained by present theories. It does appear that they are strongly affected by the sediments. The ocean bottom seismometer may offer the definitive approach to this problem. The deep submarine explosion, Wigwam, provided interesting data on this subject but was fired in an area where the structure may differ somewhat from the typical deep ocean.

1.3. Microseisms.

The sharp peak of the microseismic spectrum lies in the intermediate period range, usually falling between 4 and 8 seconds. A better understanding of these waves is of great importance to seismology. The writer believes that new experimental approaches are needed for substantial progress in this field. One of these might be the ocean bottom seismograph, another might be the study of microseisms of longer periods (10-20 seconds) in hope of learning something related to the shorter period microseisms.

Appendix 9

EQUALIZATION AND PULSE SHAPING TECHNIQUES APPLIED TO THE DETERMINATION OF INITIAL SENSE OF RAYLEIGH WAVES

John W. Tukey

1.1 Wave propagation vs. black boxes

Seismology has, naturally, been most concerned (i) with the nature of the waves arriving from earthquakes and other shocks, and (ii) with what these waves may be persuaded to tell us about the nature of the medium through which they have passed. In both these endeavours it has been natural to concentrate attention on such concepts as progressing waves, group velocity, and the transference of energy.

Today we have particular reasons to be concerned with (iii) the sense (e.g. up or down), near the source of the seismic waves, of the disturbance which proceeds in a given direction. We have to infer the nature of the disturbance near the source from a knowledge of its nature at a distance. We need to, at least approximately or crudely, undo what transmission through (possibly thousands of kilometres of) a dispersive medium has done. To this end it is natural, and wise, to think in terms of an entirely different set of concepts. We need not be concerned with the details of what happens to the disturbance on route, except as all these details are combined into an over-all transformation. We need not be concerned with the total delay suffered by the disturbance; only relative delays matter for our particular problem. And since the earth is substantially a linear medium (admits the principle of superposition), we need only consider relative delays for various frequencies. Thus the phase velocity of the seismic waves, rather than their group velocity, will be important.

This means that we may treat that part of the earth through which the waves we are studying pass, and the local environment of the seismometer, and the seismometer and its recording equipment, as a single "black box", as a linear device which attenuates and phase shifts the components of various frequencies relative to one another. Our problem is to attach a corrective "black box" to the given "black box", so that the final output will be as revealing as possible.

1.2 Favourable characteristics of long period surface waves

Problems of analysis are simplest, and prospects of success are most favourable for the case of long period surface waves. For periods of 10 seconds and up, these have wavelengths of at least 30 kilometres, and are guided waves, transmitted

in the layer of the earth bounded by the surface and the Mohorovicic discontinuity. Most local irregularities are small enough, compared to a wavelength, to have little effect. Thus, in comparison with other seismic waves, both idiosyncrasies of site and attenuation per kilometre are reduced. Recording at distant points is likely to be as satisfactory as possible.

The data-analysis problem is simpler for long period (low-frequency) waves because fewer things can affect the signal. The duration of the source will almost always be short in comparison with a period; consequently the source can almost always be treated as an impulse. (And since most sources will be close to the surface, as measured in wavelengths, the effects of focal depth will be reduced.) Consequently, the signal transmitted in a given direction will contain, and will initially be determined by, three items: a time, a direction ("up" or "down" for Rayleigh waves) and an amount.

1.3 Analyzing a simple input

From the point of view of designing data-analysis schemes, such simplicity is very desirable. The output from the given black box, i.e. the seismograph trace, is of the form

$$A_1 W(t-t_1) + A_2 W(t-t_2) + \dots + A_k W(t-t_k) + \text{noise}$$

where the times and sizes t_1, A_1, t_2 A_2, ..., t_k, A_k of the impulses are the only unknowns and $W(\tau)$ is the response of the given black box to a unit impulse. $W(\tau)$ is, indeed, usually called the impulse response, of the black box. By attaching another, corrective black box we alter the output, but only to

$$A_1 W_{12}(t-t_1) + \dots + A_k W_{12}(t-t_k) + \text{noise}^*,$$

where $W_{12}(\tau)$ is the response of the series combination of boxes to a unit impulse, and "noise*" is a somewhat altered form of "noise". We can, within limits, design $W_{12}(\tau)$ in such a way as to make this new output as revealing as possible.

Just because our original output was simple, we are left with at most two problems.

(1) shaping $W_{12}(\tau)$ to be revealing, and

(2) avoiding serious difficulty with noise.

These two problems are intrinsically interlocked, and should in principle be solved together. Fortunately, however, the noise problem for long period Rayleigh waves appears to be so far from serious that we can do quite well by solving only the first problem.

If noise were entirely absent, and if no frequency was attenuated so far that it could not be recovered, we might wish to adjust the second black box so that $W_{12}(\tau)$ would consist of a single sharp peak. In a real situation, however, some frequencies are likely to be so greatly attenuated in the first black box that any attempt to recover them would yield more noise than useful information. This is especially so for long seismic waves, where ever-present microseisms deny us effective use of an adjacent band of frequencies near 150-200 millicycles per second (near 5-6 seconds period).

With relevant frequencies excluded, $W_{12}(\tau)$ cannot be a sharp peak. A reasonable problem, when noise is not too serious, is to make it a smooth peak of moderate breadth. To do this subject to a limitation on the frequencies present, requires both

(1) holding over-all relative phase shifts to a reasonably small value, and

(2) shaping the relative attenuation curve correctly.

1.4 Phase equalization

Since the outputs we observe come from impulsive inputs, and since Fourier analyses of outputs would yield both amplitude and phase information, we could try to obtain information on relative phase shifts and relative attenuations by Fourier analysis. Having found the relative phase shifts, we would then have the soluble, but not trivial, problem of synthesizing a corrective black box which would generate equal and opposite relative phase shifts.

Fortunately, we can avoid the complexities and details of such an approach. Especially so long as we are concerned with investigation and exploration rather than with extensive field use, it will be very helpful to simulate the second black box on a digital computer. And, as we shall see, there is a simple way to simulate the required phase compensation digitally.

As discussed in more detail in Annex A, the procedure of moving cross-correlation (cross-correlation at varying lags), when applied to (i) a function approximating the impulse response of the first black box and (ii) the trace being corrected, leads to a time function (a function of lag) which is approximately free of relative phase shift. Every simple earthquake of substantial magnitude offers us, in its seismograph trace, the impulse response for a reference black box which stretches from its source to its seismograph trace. If the black box from the source of the

shock being studied to the trace of the same seismograph is well approximated by this reference black box, then moving cross-correlation of reference trace with the trace under study will provide the phase-correction portion of the desired, corrective black box by very nearly compensating for all relative phase shifts.

More specifically, h (t), where

$$h(\tau) = \sum f(t-\tau)g(t),$$

f(t) is the fixed reference trace, and g(t) is the trace being analyzed,

(1) will be nearly free of phase shift, and

(2) will have suffered relative attenuations by factors which are the squares of those for the initial black box.

The trials to be reported below indicate that the matching of earth paths required to obtain useful phase compensation by this method may not be at all critical.

Further phase adjustments, based upon either empirical trial or theoretical understanding, can of course be superimposed upon the result of such moving cross-correlation, as can amplitude adjustments to improve the pulse shape.

1.5 Pulse shaping

If we have a signal which involves only frequencies between f_0 and f_1, and ... frequency components have zero relative phase shift, the shape of the signal depends only upon the amplitudes with which the various frequencies appear.

Both flat and shaped amplitude distributions, and the corresponding pulse shapes = impulse responses, are shown in Figures A and B for bandwidths of 2 and 3 octaves, respectively.

The particular shapes of amplitude vs. frequency shown in the lower parts of Figures A and B produce very usable pulse shapes. It would seem, for the present, much more worthwhile to realize these than to find still smoother shapes.

If we have chosen the relation of amplitude to frequency which we desire to use, and have a trial version of the compensating black box available, we can study its amplitude-vs-frequency performance quite easily. We have only to pass samples of the signals (traces) to be studied through the trial second box and calculate the spectrum of the final output. This spectrum will be the square of the amplitude-vs-frequency characteristic. Thus deviations from desired performance can be easily assessed.

The design and application, in a digital computer not forced to work in real time, of filters which change relative attenuations without changing relative phases is not difficult. Accordingly, comparisons of actual output spectra with desired spectra can lead rather directly to readjustments of the corrective black box which will bring the actual amplitude-vs-frequency response close to that desired.

1.6 Sample results

Some very preliminary trials have been made of the general approach.

Digitized values for vertical long period seismograph traces for 4 earthquakes (located in California or Baja California) were furnished by Dr. Jack Oliver and Mr. Paul Pomeroy of the Lamont Geological Observatory, as indicated in Table 1, (Waynesburg, Pa. is an out-station of the Lamont Observatory, and uses an equivalent vertical seismometer).

TABLE 1

#	Earthquake Co-ordinates	Date	Time	Distances and lengths of record* Palisades	Waynesburg	Quality of record **	Magnitude *** P	B
I	37.9N, 122.6W (Marin Peninsula)	22 Mar. '57	19-14-22	4140 km (510 pts)	~3700 km (540 pts)	Good	5.25 5.50	
II	31.5N, 115.5W (S of Mexicali)	25 Aug. '56	15-57-43	3885 km (250 pts)	--	Inter-mediate	4.9	
III	35.5N, 121W (Nr. Morro Bay)	16 Nov. '56	03-23-05	3706 km (220 pts)	--	Poor	4.75	5.0
IV	37.5N, 121.8W (Nr. Calaveras Reservoir)	31 Oct. '58	00-26-15	~4000 km (440 pts)	--	Very poor	--	4.2

* Points were read every 2 seconds. Noise periods were visually estimated as 6, 7, 7.5 and 4+ seconds at Palisades and 7.5 seconds at Waynesburg.

Nyquist frequency 0.25 cycles per second = 250 millicps.

** Free period of seismometer ~15 sec.
Free period of galvanometer ~80 sec.
Peak magnification ~2000.
Readings given to 0.1 mm.
Very poor = "in fact, no trace deflection is evident on the record from this instrument."

*** P = Pasadena, B = Berkeley

The most suggestive results to date were obtained by:

(1) the use of numerical filtering to nearly remove frequencies above 100 millicps (periods below 10 seconds), and,

(2) the use of Waynesburg I as the reference trace in forming moving cross-correlations with the Palisades records.

The results for Palisades I, II, III, and IV are shown (not to the same vertical scale) in Figures C, D, E, and F. The existence in all four cases, and the relatively high similarity of appearance (except for sign) of the most distinctive feature -- a sharp spike of one sense between two, somewhat weaker but still substantial, spikes of the other sense -- is surprising. We are clearly able to establish the relative senses, near the source, of the disturbances propagated toward Palisades, namely:

Earthquake	Sense relative to I	
	Main pulse	Other shocks; higher modes, echoes, etc.
I	+	none obvious
II	-	(-) possible
III	-	- (which is main?)
IV	+	-

It is clear that, even with the present techniques, the sense of "initial disturbance near the source as propagated in the direction of observation" can certainly be determined for shocks considerably weaker than Earthquake III, and, possibly, for shocks as weak as Earthquake IV. It is reasonable to expect improvements in technique, through better pulse shaping and phase compensation, etc., to considerably lower the threshold of sensitivity.

Until we know more about the relation of conventional earthquake magnitude to Rayleigh intensity in various directions, which will require moderately extensive exploratory analyses of records from various stations, it will be hard to say where the cut-off of sense determination by the present technique will fall. Probably some earthquakes of magnitude 4.0 will reveal senses of initial motion at these distances. Improvements in technique, within the general approach, may lower this limit further, how far is hard to judge.

1.7 Suggestions for further study

The initial results of this "communication theory" approach have been sufficiently striking to suggest exploration of the use of similar techniques on other types of seismic waves, as well as more extended and careful application of such techniques to long period Rayleigh waves. Presumably the next most promising candidate for study is the P-wave, whose "initial motion", when detectable from the raw trace, provides the standard criterion for short-range detection.

How is it reasonable to try to use related ideas to make the "initial motion" of the P-wave detectable at ranges closer to the P-wave shadow zone? The approach used for long period Rayleigh waves cannot be applied without modification, because the regular initial appearance of the P-wave is, before long, obscured by reflected and refracted waves of various sorts. Only the first portion of the P-wave record can be freely processed. However, as discussed briefly in Appendix B (Section 1.B4), it may well be possible to apply a modification of the approach used above.

A second alternative would be the use of phase compensation based on our general knowledge of the relation of phase velocity to frequency for those frequencies important in the first portion of the P-wave. Both of these possibilities clearly deserve study.

Exploration of possible applications to waves of other types and frequencies cannot be wisely blueprinted in detail, but should clearly be undertaken.

We need to know many things about the application to long period Rayleigh waves, including:

(1) How do the senses obtained in a given direction for long period Rayleigh waves and P-waves compare?

(2) Does the typical earthquake send Rayleigh waves into different sectors with different senses of initial motion?

(3) How critical is the matching of the earth paths for the reference trace and the trace to be analyzed?

(4) Will other paths than California-New York produce as satisfactory results?

(5) How many reference traces will be required at a typical seismograph station?

(6) How much will improved phase correction and pulse shaping improve the recognizability of sense?

It would be easy to add other relevant questions, but these should serve to illustrate some of the directions of profitable inquiry.

If further studies continue to be encouraging, consideration should be given to trying out a single tripartite installation located near the centre of the North American continent with long period seismometers at three good sites forming a triangle of sides 50-100 km. To what extent can one such installation monitor earthquakes all over the continent?

1.8 Acknowledgements

The 704 programme was written by Miss Ruth A. Weiss, who, together with Miss Shirley J. Reed, supervised the computations. Annex C is based directly on material prepared by my colleague at Murray Hill, Ralph Blackman.

Appendix 9a

THE PHASE COMPENSATION METHOD OF EQUALIZATION

Jack Oliver

In an earlier part of Appendix 9, Dr. Tukey discussed the "black box" method of equalization. This method is equivalent to determining empirically the effect which the propagating medium and the seismograph have had on the recorded wave train, and then applying this effect inversely to similar trains in an effort to learn more about the sense of the pulse in the vicinity of the source. The method, at present, is best applied to long-period surface wave trains. No attempt is made to understand or specify mechanisms which determine the characteristics of the black box, nor is there a need to do this. Although this method offers great promise, it does not eliminate the desirability of attempting to understand the black box.

Once phase velocities have been determined over an entire continent, or over the whole world, phase compensation can be based upon well-understood properties of the earth, rather than upon the empirical behavior of waves from another earthquake. Determinations of phase velocity are essential if such a desirable possibility is to become practicable. This Annex describes the method of determining phase velocities and describes a simplified method of seismogram-analysis which permits one to subtract the effects of these mechanisms from the recorded seismic wave train and thus arrive at information on the sense of the seismic pulse at or near the source. This method was suggested by Mr. James Brune and developed by Mr. Brune, Dr. John Nafe and the writer at the Lamont Observatory.

A seismic pulse at the origin may be synthesized from many travelling Fourier components of different amplitude and phase. The dispersed, long-period, seismic wave train at some distance from the source at a later time may also be synthesized in the same manner. If the amplitudes within the train vary slowly with frequency, then the principle of stationary phase may be applied. This principle states that the chief contribution to the wave train at a given point comes from that very narrow band of frequencies for which phase is stationary. Thus, one may fix the

phase of a single frequency component at that particular time and place. The phase of this component, and similarly every other component recorded, can then be determined at the origin at zero time if the phase velocity over the entire path and the instrumental phase shift are known. Instrumental phase shift may be found with no difficulty, for current methods of obtaining this are adequate and only a refinement of present operational methods of calibration of long-period instruments is required. With the exception of much of the United States, where some preliminary measurements have been carried out, phase velocity as a function of frequency is not generally known for regions throughout the world.

The United States results, however, demonstrate that such a study is possible and is feasible with a network of stations such as that proposed by the Geneva Conference, providing long-period instruments are operational at all stations. The method requires a network so that individual phases of the seismic wave train may be traced across a given interval. Once the Geneva network is installed, or once any network of reasonably uniform instrumentation is installed, phase velocity data can be obtained fairly quickly after a few earthquakes are recorded.

The application of Brune's method is quite simple. It has the advantage that the calculations can be carried out by hand in a few minutes. A few preliminary studies have already been made using existing earthquake data and results are very promising.

At present, instrumentation in the United States is such that phase velocity studies may be made only for extremely large earthquakes in ideal locations. When the instrumental situation here is improved, as proposed elsewhere in this report, phase velocity studies should be carried out in as much detail as possible in the U.S. to determine the ultimate capability of the method and to perfect techniques for use in other regions. In the meantime, much can be accomplished from the study of well-located shocks recorded at individual stations at a moderate distance from the epicenter.

Annex A to Appendix 9

PHASE COMPENSATION

John W. Tukey

In studying the "black box" provided by the earth between a specific shock origin and a specific observation point, we have one unusual advantage, of which we should make full use. Many earthquakes, and apparently almost all small earthquakes, produce disturbances which are initially of very short duration. In comparison with the periods of the waves which are likely to be most easily analysed, the initial disturbance is an impulse. This offers us two distinct advantages (at least from the data analyst's point of view): (i) We cannot expect to learn anything about the initial disturbance (as propagated in a definite direction) except its sign and magnitude, and can thus abstain from fruitless efforts to learn about its shape. (ii) We are provided, gratis, with many measurements of the impulse response of our black box, since each received signal is, except for superposed noise, its impulse response. This "black box" consists of the combination of many kilometres of rock, any idiosyncrasies of local structure near the seismometer, the seismometer, and the recording equipment.

The fact that a certain relative phase shift (between two frequencies) may have been spread through thousands of kilometres of rock, or may have been concentrated in the dynamics of the seismometer suspension, need not concern us. We are to infer the sign of the initial, nearly-impulsive, disturbance from the record we have. A phase-shift is a phase-shift wherever it may occur. And, wherever it may occur, it affects both the record and our problem of using the record to see the original disturbance in the same way.

1.A1 Conventional machinery

We now need to set up some of the conventional machinery for the description of "black-boxes" which are linear, in the sense that their output for superposed inputs is the superposition of their outputs for the separate inputs, and time-invariant, in the sense that delaying an input by any fixed amount delays the output by the same amount, but does not change its size or shape. When we operate in the time domain, such a black-box is described by its impulse response $W(\tau)$

which relates input to output thus:

$$y(t) = \int W(t-t')x(t')dt'$$

where $x(t')$ = input at input time t',

$W(t-t')$ = impulse response at relative time $t-t'$,

$y(t)$ = output at output time t.

We have here modified the conventional relation by allowing the use of two different times to discuss input and output. This is not important, but is convenient, since it allows us to avoid the large, inessential phase shifts associated with mean or typical travel times from source to observation.

If we wish to describe a linear, time-invariant black box in the frequency domain, we use the transfer function $Y(f)$, where $\omega = 2\pi f$ relates angular frequency ω to frequency f. $Y(f)$ has, in general, complex values and the property that a sinusoidal input

$$a \cos (\omega t' + \phi)$$

corresponds to a sinusoidal output

$$|Y(f)| \cdot a \cos (\omega t + \phi + \theta(f))$$

where

$$Y(f) = |Y(f)| e^{i\theta(f)}$$

Thus, $\theta(f)$ describes the phase-shift, while $|Y(f)|$ describes the amplification or attenuation of the black box.

The mutual relationship of these two modes of description is exhibited by the relations

$$Y(f) = \int_{-\infty}^{+\infty} W(\tau) e^{-i\omega\tau} d\tau$$

and

$$W(\tau) = \int_{-\infty}^{+\infty} Y(f) e^{i\omega\tau} df.$$

These, then are the standard tools for describing a linear, time-invariant black box.

1.A2 Phase-correction

With these definitions, the record of an earthquake takes the form

$$y_j(t) = b_j W_j(t) + N_j(t)$$

where

b_j = the impulsive disturbance near the j^{th} earthquake, as propagated in the direction toward the seismometer,

$W_j(t)$ = the impulse response of the "black box" between the site of the j^{th} earthquake and the record,

$N_j(t)$ = whatever superposed "noise" (microseisms, factory vibrations, electronic amplifier noise, etc.) appears superposed on the record from the j^{th} earthquake.

Let us, for the present, neglect $N_j(t)$, and consider how we may phase-equalize (i.e., correct for phase-shift) our signal $y_j(t)$.

If we were to pass $y_j(t)$ through another black box, whose impulse response was

$$W_j'(\tau) = W_j(-\tau)$$

and whose transfer function was, consequently

$$Y_j'(f) = Y_j(-f) = (Y_j(f))^*$$

where * represents taking the complex conjugate, the over-all transfer function of the two black boxes in series would be

$$Y_{12}(f) = Y_j'(f)Y_j(f) = |Y_j(f)|^2 \geq 0.$$

We see that $Y_{12}(f)$ is real and non-negative, so that there are no relative phase-shifts from the combination of the black boxes. The second black box has phase-equalized the first, at a cost of squaring the relative attentuation or amplification of the various frequencies.

Because of this amplitude distortion, the output, which we may call $z(t)$, from the second black box will not be a sharp pulse, but it will be symmetric. Moreover, since (i) the expansion of the initial sharp pulse into a superposition of $b_\omega \cos\omega t$ terms will involve b_ω's all of the same sign as b_j, and (ii) $Y_{12}(f)$ is not only real but positive, all the $Y_{12}(f).b_\omega \cos\omega t$ terms whose superposition is $z(t)$ will have $Y_{12}(f).b_\omega$ products of the same sign as b_j. Thus the sign of $z(0)$ will be the same as that of b_j, and $z(0)$ will be a maximum or minimum, according to the sign of b_j.

1.A3 Realization

The results of the last section were based on our being able to realize a second black-box with

$$W_j(t) = W_j(-\tau)$$

How are we to do this? If we possess knowledge of $W(t)$ this may be easily done. For the second black-box may then be a digital computation.

If we put

$$(*) \qquad z(t) = \sum_{\upsilon} W_j(\upsilon h - t)y(\upsilon h)$$

where h is a conveniently short time step, then we will realize $W_j'(\tau)$. For if $\gamma(\nu h)$ should equal 1 for $\nu=0$ and vanish for other values of ν, then $z(t)$, which would be the impulse response of formula (*), would be $W_j(-t)$. Our problem then resolves itself into obtaining $W_j(t)$, at least for t a multiple of h, or a reasonable facsimile thereof.

We seek values of $W_j(t)$. The record of the k^{th} earth shock gives us values of

$$y_k(t) = b_k W_k(t) + N_k(t).$$

What happens if we use $y_k(\nu h)$ as reasonable facsimilies of $W_j(\nu h)$?

If the effect of the noise be negligible, and the sites of the j^{th} and k^{th} earth shocks are close enough so that $W_j(t) \approx W_k(t)$, we find, by the same arguments, that (i) z(t) is symmetric about a center, say t=c, (ii) z(c) is a maximum if positive and a minimum if negative, (iii) the sign of z(c) is that of $b_j b_k$.

Thus, if noise influences are not too great, we can tell from the sign of z(c) whether or not the initial disturbances from the j^{th} and k^{th} earth shocks had the same sign. Clearly, this is the most that we could expect from a purely black box approach.

1.44 Effects of mismatch

We need next to consider the structure and origin of the relative phase-shifts in somewhat more detail. Let us write

$$\theta_j(f) = \varphi_j(f) + D_j\eta_j(f) + \psi_j(f)$$

where, for the j^{th} shock and the earth path,

$\theta_j(f)$ = overall phase shift,
$\varphi_j(f)$ = phase shift near the source,
D_j = distance from source to seismometer,
$\eta_j(f)$ = average phase shift per unit distance while in transit,
$\psi_j(f)$ = phase shift near the seismometer.

The phase shift remaining, when the trace of the k^{th} earthquake is used to process (by moving cross-correlation) the trace of the j^{th} earthquake is,

$$\theta_j(f) - \theta_k(f) = \varphi_j(f) - \varphi_k(f) + D_j\eta_j(f) - D_k\eta_k(f) + \psi_j(f) - \psi_j(f)$$

One of the most plausible assumptions we can make is that $\psi_j(f) = \psi_k(f) = \psi(f)$. Indeed it is not unlikely that both $\psi_j(f) = \psi_k(f) = \psi(f)$ and $\eta_j(f) = \eta_k(f) = \eta(f)$ are bearable approximations. If they are,

$$\theta_j(f) = \theta_k(f) = (D_j - D_k)\eta(f)$$

and we may compare the analyzed output to that expected in the free earth at a distance $D_j - D_k$ from the shock; the phase shift for this comparison situation being

$$\psi(f) + (D_j - D_k)\eta(f)$$

Thus using a reference trace for an earthquake at distance D_k to analyze one at distance D_j rolls back the phases, not to the beginning, but to where they would be after propagating a distance $D_j - D_k$, if there had been no phase shift near the source.

1.A5 "Shimming up" the phase correction

If the approach discussed here is to be used routinely in an extensive field program, the number of different reference traces required for use at each station is an important number. One way in which it might be reduced would be the superposition of small empirically chosen phase adjustments on top of the phase adjustment made by moving cross-correlation with a reference trace. Such phase-adjustment by "shimming-out" clearly deserves some attention, especially if extensive field use of the approach is contemplated.

1.A6 Further adjustments

In addition to correcting phases, we must give attention to amplitudes, eliminating frequency regions with unfavorable signal to noise characteristics, and, for best performance, shaping the amplitude response within the accepted frequency interval to yield a smooth pulse. For long period seismic waves, the main effort of elimination will be directed toward the frequency range containing microseisms. Since these lie at somewhat higher frequencies, the required filtering will have the general nature of smoothing.

In addition to such smoothing, we may desire to eliminate the very lowest frequencies (see Annex B, Section 1.B3 for mention of some of the relevant techniques).

Finally we may wish to shape our pulses. (As yet this area has not been explored).

Annex B to Appendix 9

NUMERICAL TECHNIQUES

John W. Tukey

1.B1 Fourier transformation

Digital Fourier transformation is likely to arise in connexion with the approach described in this Annex either directly or indirectly.

It arises directly in connection with estimation of the phase relations in a trace, and indirectly in connection with the estimation of spectra and cross-spectra by the usual digital techniques. The same two considerations, aliasing and window-shaping, are of vital importance in both situations.

If observations, mean lagged products, or values of a mathematically specified function are only available at given equal intervals, say of length Δt, then there is inevitable "aliasing". If we define the Nyquist or folding frequency by

$$f_{Ny} = \frac{1}{2\Delta t}$$

then all frequencies

$$f,\ 2f_{Ny} - f,\ 2f_{Ny} + f,\ 4f_{Ny} - f,\ 4f_{Ny} + f,\ \ldots$$

are precisely and irretrievably indistinguishable. This has two important practical consequences:

(1) it will do us no good to carry any numerical frequency analysis beyond $f = f_{Ny}$, and

(2) in interpreting the result of any frequency analysis, including spectral and cross-spectral analyses, we must always remember that aliasing may have been responsible for some or all of the phenomena we have noted.

Indeed, the two situations are so similar that, if we have a cross-spectral programme available, and desire to do only a few Fourier transformations, it may pay us to do them by making cross-spectral analyses for combinations of each given series with an artificial series of which only one value is not zero, since this will save programming time (at the expense of machine time).

1.B2 Cosine tapers

Records for analysis are likely to start abruptly and end abruptly, in fact it is hard at first sight to see how it could be otherwise. The human eye is rarely bothered by the fact that there is a first point on the left of the picture, and a last point on the right; indeed the eye is far more used to records of finite length than to records which go on and on without end. But the mathematical formula is much more likely to be bothered by starts and stops. Indeed, all formulas which are related, even distantly, to a Fourier transformation tend to behave as if there were many zeroes in front of the first actual value, and many zeroes behind the last actual values.

Such formulas regard the data, whether we like it or not, as of the form

$$f(t) = h(t) \cdot B(t)$$

where h(t) is defined for all time, and represents the complete possible record, and where B(t), the data window or "snipping function" vanishes for t's other than those for which we actually have, and are using, data. Multiplication on one side of a Fourier transform corresponds to convolution on the other side. In particular, multiplication of time functions corresponds to convolution of frequencies, so that the frequency components of f(t) are those of h(t), shifted in frequency by the frequencies which appear in B(t).

The Fourier transform of

$$B_1(t) = \begin{cases} 1, & |t| < t_o \\ 0, & \text{otherwise} \end{cases}$$

is

$$b_1(f) = 2 \cdot \frac{\sin 2\pi t_o f}{2\pi t_o}$$

and is substantial, and oscillatory, for rather large f. Consequently, its use as a data window disturbs frequencies unnecessarily, since it introduces unnecessarily large frequency shifts.

The Fourier transform, $b_2(f)$, of

$$B_2(t) = \begin{cases} \frac{1}{2}\left(1 + \cos \frac{\pi t}{t_o}\right), & |t| \leq t_o, \\ 0 \quad , & \text{otherwise}, \end{cases}$$

has a broader major lobe, but becomes and remains small for much lower frequencies than $b_1(f)$. Consequently the use of $B_2(t)$ as a data window, or "snipping function", disturbs frequencies much less than does the use of $B_1(t)$. Its use may be referred to as the use of a cosine taper.

Less gentle cosine tapers are provided by instances of

$$B_3(t) = \begin{cases} 1, & |t| \leq t_1 \\ \frac{1}{2}\left(1 + \cos \frac{\pi(t-t_1)}{t_o - t_1}\right), & t_1 \leq |t| \leq t_o \\ 0, & \text{otherwise}, \end{cases}$$

which reduces to $B_1(t)$ when $t_1 = t_o$ and to $B_2(t)$ when $t_1 = 0$.

1.B3 Elimination of very low frequencies

In many, if not most, analyses of time series, special attention has to be given to slow variations. This is the case, whether one speaks of "trends", "very low frequencies" or "zero frequency contributions". While these slow variations may be qualitatively different from the faster ones, as might, for example, be the case for certain sorts of recorder misalignments, they are often qualitatively the same. Even then it is often necessary to use special care to "eliminate" them before analyzing the more rapidly varying constituents, just because the slowly varying constituents are likely to be so large, relatively, as to confuse the later analysis.

In moving cross-correlation or spectral analysis a number of different devices may be used to avoid complications from very low frequencies. In order of increasing efficacy, the most common are:

(1) The use of "corrections for the mean" in evaluating moving sums of cross-products, e.g. computing

$$h(\tau) = \sum_{1}^{N} f(t_i - \tau)\ g\ (t_i) - \frac{1}{N} \sum_{1}^{N} f(t_i - \tau) \sum_{p}^{N} f(t_i)$$

instead of merely

$$h(\tau) = \sum_{1}^{N} f(t_i - \tau)\ g\ (t_i).$$

(2) The fitting of a best or nearly-best straight line to the observations, and the analysis of the deviations of the observations from this line.

(3) The fitting of a best or nearly-best polynomial of given degree to the observations, and the analysis of the deviations of the observations from this line.

It will rather often prove desirable to preface (1), or follow (2) or (3), with multiplication by a cosine taper in order to avoid additional low frequency contamination due to the non-zeroness of the first and last points.

1.B4 Possible analysis of P-waves

If we desire to investigate phase-compensation procedures for dealing with the initial section of the P waves, we face new difficulties. After a certain time, the record of the P waves is contaminated by the arrival of waves of other types. It does not matter for the present purpose whether these are reflections or refractions of P waves, or whether they are wave trains of some other character. Their relative times of arrival will depend strongly on the precise location of the source, and, as a consequence, any attempt to describe the received signal in terms of phase shifts will require rapid gyrations of phase for relatively small changes in source location. This we must avoid at all costs.

The only way to avoid difficulty with these later-arriving wave trains is to snip off the record before they arrive. Snipping it off abruptly will disturb frequencies unnecessarily. Since we are interested in phase compensation depending on frequency, unnecessary disturbance of frequencies is undesirable. Thus the use of a tapered "snipping function" or data window is indicated. A gentle cosine taper seems likely to be the practical solution.

The step-by-step procedure which might be applied is the following:

(1) Choose a time origin near the beginning of the P wave.

(2) Choose a t_o such that one can be fairly certain that no other types of waves will arrive before time t_o.

(3) Obtain digitalized values from the record for $-t_o \leq t \leq t_o$. (At sufficiently close intervals.)

(4) Multiply these by

$$\tfrac{1}{2}(1 + \cos \frac{\pi t}{t_o})$$

(5) Treat the sequence of values consisting of zeroes for $|t| \geq t_o$, and the products from Step 4 for $|t| \leq t_o$, as a pseudo-record, and take it on to further analysis along the lines of the treatment of long period Rayleigh waves.

1.B5 Smoothing by 3's and 5's

The formation of moving averages, or of moving sums, has long been recognised as a very convenient numerical technique. In smoothing by 3's, for example, we replace the sequence of values x_t by the sequence

$$y_t = x_{t+1} + x_t + x_{t-1}$$

or by some constant multiple of these y_t. In the present connection it is important to understand the behaviour of such smoothing processes in terms of frequency, attenuation and phase shift.

Smoothing with a symmetrical set of coefficients, as in the example above, of course produces no phase shifts at any frequency.

Smoothing by 3's clearly provides infinite attenuation for some frequencies, since a sine or cosine wave of period 3 is clearly annihilated. Smoothing by 5's annihilates sines and cosines of period 5 and those of period 5/2 = 2.5. Smoothing first by one and then by the other will annihilate all three of these frequencies.

More quantitative information about attenuation is easily obtained along the lines discussed in 1.C2. Figure G shows the relative attenuation of different frequencies caused by

(1) smoothing by 3's,

(2) smoothing by 5's,

(3) smoothing first by one and then by the other, in either order.

1.B6 Sources and examples

The approach outlined in this Annex relies on the concepts and attitudes of linear communication theory. It is closely related to many of the concepts involved in spectral analysis, although it diverges widely from most uses of spectral analysis by focusing interpretation upon a time function rather than a frequency function. Its use, on the other hand, is often wisely guided by what can be learned from spectral or cross-spectral analysis.

Those interested in applying or extending it may therefore find sources related to spectral analysis of assistance. The following four references cover much of what is known about simple spectral analysis, and say a little about cross-spectral analysis. They tend to emphasize that particular theory of sampling fluctuations which is appropriate when spectral analysis is applied to Gaussian noises. This part of the discussion is wholly irrelevant to, (and, specifically, far too pessimistic for) the situation contemplated in this Annex, where the original input consists of well separated impulses. (Though it may be quite relevant in spectral analysis of microseisms.) Those using these references as background material for the problem of this Appendix may skip all the sampling variability discussion, and must not allow it to discourage them.

(1) H. Press and J.W. Tukey "Power spectral methods of analysis and application in airplane dynamics:, Vol. IV, Part IV C AGARD Flight Test Manual, E.J. Durbin, ed. North Atlantic Treaty Organization, June 1956, pp. IVC:1 - IVC:41. (Also Bell System Monograph 2606.) (Sketches both simple and cross-spectral cases).

(2) J.W. Tukey "An introduction to the measurement of spectra" to appear in Studies in Probability and Statistics, to be published by Almquist Wiksell, Stockholm. (An account of the considerations involved in planning and making measurements of near-Gaussian processes.)

(3) J.W. Tukey, "The Estimation of (power) spectra and related quantities": pages 391-411 of On Numerical Approximation, ed. Rudolph E. Langer, University of Wisconsin Press, 1959. (An account slanted toward mathematicians interested in numerical computation.)

(4) R.B. Blackman and J.W. Tukey, "The measurement of power spectra from the point of view of communications engineering," 37 Bell System Technical Journal, 183-282 and 485-569 (1958) (also published separately by Dover, New York, 1959). (A detailed account of the background and details of spectral analysis of individual time functions.)

No extensive expository account of cross-spectral analysis seems to be available. The sampling theory for jointly Gaussian signals, which is far from relevance here, has been treated mathematically in

(5) N.R. Goodman, "On the joint estimation of the spectra, cospectrum and quadrature spectrum of a two-dimensional stationary Gaussian process." Scientific Paper No. 10, Engineering Statistics Laboratory, New York University, 1957, (Also Ph.D. Thesis, Princeton University).

Annex C to Appendix 9

SYNTHESIS OF DIGITAL PHASE COMPENSATORS

John W. Tukey

1.C1 The method of frequency transformation

Theory and practice in the synthesis of filters and corrective devices is still concentrated in the continuous-time (analog) area. When we work with discrete time, as we must in digital systems, it is often convenient to throw discrete time problems back into continuous ones. We may do this by the "method of frequency transformation," by introducing a fictitious continuous-time angular frequency υ, an angular pseudo-frequency, by

$$(*) \qquad \upsilon = \frac{2}{\Delta t} \tan \frac{\omega \Delta t}{2}$$

where Δt is the time interval between successive discrete times. The corresponding pseudo-frequency will be $g = 2\pi\upsilon$.

A wisely arranged discrete-time system will have filtered out frequencies above the folding or Nyquist frequencies $f_{Ny} = 1/(2\Delta t)$ before sampling. Consequently $|\omega \Delta t/2| \leq \pi/2$ for all relevant ω, so that there will be no difficulty with the periodicity of the tangent.

If a desired filter characteristic (i.e. transfer function) is given as a function of ω, this transformation allows us to state the corresponding pseudo-characteristic as a function of υ. If we then approximate this pseudo-transfer function by a rational function of $p = i\upsilon$, say $R(i\upsilon)$, we may return to real time by considering

$$F\left(\frac{2i}{\Delta t} \tan \frac{\omega \Delta t}{2}\right) = R\left(\frac{2}{\Delta t} \frac{1-q}{1+q}\right)$$

where $q = e^{-i\omega\Delta t}$. Any rational function of q, as we shall see, is the transfer function of an easily realizable digital filter-or-compensator. If we synthesize this corresponding discrete-time linear operation, its transfer function will approximate our desires to the same extent that $R(i\upsilon)$ approximated the desired pseudo-transfer function. Thus the problem of designing a discrete time filter-or-compensator is reduced to the classical problem of designing a continuous-time filter-or-compensator.

1.C2 Linear operations in discrete time

The simplest linear (and time invariant) operations in discrete time are those usually referred to as moving averages, where, explicity,

$$y_k = a_o x_k + a_1 x_{k-1} + \cdots + a_n x_{k-n}$$

The corresponding transfer function is to be found by substituting

$$x_k = e^{i\omega k\Delta t}$$

$$x_{k-j} = e^{i\omega k\Delta t}(e^{-i\omega\Delta t})^j = q^j e^{i\omega k\Delta t}$$

whence

$$y_k = e^{i\omega k\Delta t}(a_o + a_1 q + \cdots + a_n q^n)$$

so that the corresponding transfer function is

$$Y(\omega) = a_o + a_1 q + \cdots + a_n q^n$$

with, as before

$$q = e^{-i\omega\Delta t}$$

We can also consider autoregressive (or recursive) linear operations which may be written as

$$a_o z_k + a_1 z_{k-1} + \cdots + a_n z_{k-n} = y_k$$

or as

$$z_k = \frac{1}{a_o} y_k - \frac{a_1}{a_o} z_{k-1} - \cdots - \frac{a_n}{a_o} z_{k-n}$$

each of which exactly undoes the work of the corresponding moving average. As a consequence their transfer functions are exactly the reciprocal of those for the corresponding moving averages, namely

$$Y_{zy}(\omega) = \frac{1}{Y_{yx}(\omega)} \qquad \frac{1}{a_o + a_1 q + \cdots + a_n q^n}$$

If we "follow" a moving average by an autoregressive operation with different coefficients, e.g., if we use the combined relation

$$b_o z_k + b_1 z_{k-1} + \cdots + b_n z_n = a_o x_k + a_1 x_{k-1} + \cdots + a_n x_{k-n}$$

which may be written

$$z_k = \frac{a_o}{b_o} x_k + \cdots + \frac{a_n}{b_o} x_{k-n} - \frac{b_1}{b_o} z_{k-1} - \cdots - \frac{b_n}{b_o} z_{k-n}$$

We shall realize a linear operation from x to z whose transfer function is

$$\frac{a_o + a_1 q + \cdots + a_n q^n}{b_o + b_1 q + \cdots + b_n q^n}$$

a general rational function of q.

1.C3 Considerations specific to the design of phase (delay) equalizers

We now set down some general considerations on the design of rational functions which affect phase (and delay) but do not affect amplitudes. In our particular application these rational functions would be used to approximate the pseudo-transfer function of the pseudo-frequency $2\pi\upsilon$, or of the angular pseudo-frequency υ. For algebraic convenience we shall exhibit them as rational functions of $p = i\upsilon$.

The transfer function of a delay (or phase) equalizer is of the form

$$Y(2\pi\upsilon) = \frac{F(-p)}{F(p)}$$

where F(p) is analytic in $\mathrm{Re}[p] \geq 0$. Thus, $|Y(i\upsilon)| = 1$ for all real values of υ.

If F(p) is a polynomial, then $Y(2\pi\upsilon)$ may be resolved into factors of the form

$$\frac{\alpha - p}{\alpha + p} \quad \text{or} \quad \frac{\alpha^2 + \beta^2 - 2\alpha p + p^2}{\alpha^2 + \beta^2 + 2\alpha p + p^2}$$

where , 0. Thus, the phase (2) will be a sum of terms of the form

$$2 \tan^{-1} \frac{\upsilon}{\alpha}$$

one for each linear-over-linear factor, and pairs of terms of the form

$$2 \tan^{-1} \frac{\upsilon+\beta}{\alpha} \quad 2 \tan^{-1} \frac{\upsilon-\beta}{\alpha}$$

one for each quadratic-over-quadratic factor, where each $\tan^{-1}$ is to be taken between $-\pi/2$ and $+\pi/2$ (when expressed in radians).

In some connections it may be convenient to focus our attention upon relative time delays ("group delays" not "phase delays") rather than upon relative phases. The basic relation

$$\text{delay} = \frac{d\varphi}{d\omega}$$

is conveniently supplemented by pseudo-delay $= \frac{d\varphi}{d\upsilon}$,

since

$$\frac{d\varphi}{d\omega} = \frac{d\varphi}{d\upsilon}\,\frac{d\upsilon}{d\omega}$$

and

$$\frac{d\varphi}{d\omega} = \frac{2}{\Delta t}\sec^2\frac{\eta\Delta t}{2} = \frac{2}{\Delta t} + \frac{\upsilon^2}{4}\Delta t$$

we have

$$\text{delay} = \left(\text{pseudo-delay}\right)\cdot\left(\frac{2}{\Delta t} + \frac{\upsilon^2}{4}\Delta t\right)$$

The pseudo-delay $d\varphi/d\upsilon$ will be the sum of terms of the form

$$\frac{\frac{2}{\alpha}}{1 + \left(\frac{\upsilon}{\alpha}\right)^2}$$

one for each linear-over-linear factor, and pairs of terms of the form

$$\frac{\frac{2}{\alpha}}{1 + \left(\frac{\upsilon+\beta}{\alpha}\right)^2} + \frac{\frac{2}{\alpha}}{1 + \left(\frac{\upsilon-\beta}{\alpha}\right)^2}$$

one for each quadratic-over-quadratic factor. Thus the pseudo-delay is a positive rational function of υ^2, which vanishes like $1/\upsilon^2$ as $\upsilon \to \infty$. Consequently the delay will be a positive rational function of υ^2, which is bounded as $\upsilon \to \infty$, $\omega \to \pi/\Delta t$, $f \to 1/2\cdot\Delta t$.

Reasonable phase or group-delay characteristics can be synthesized with moderate ease using these relations.

Annex D to Appendix 9

SOME DETAILS OF ANALYSIS

John W. Tukey

This appendix discusses briefly (i) the actual numerical processing of the data, (ii) an inquiry into the need for such relatively sophisticated analysis, and (iii) some interesting appearances of the data at their present state of analysis.

1.D1 General structure of computations

The basic computing tool was a slightly modified IBM 704 spectral analysis program which accepted two sets of "data" of the same length, and produced

(1) sums of lagged cross-products (adjusted for means) for lags from -m to +m,

(2) mean lagged products for each series separately, and the even and odd parts of the mean lagged cross-product function, all for lags 0 to m,

(3) raw spectral estimates, simple and cross, for m+1 equally spaced frequencies, ranging from zero to the Nyquist or folding frequency (250 millicps for our data),

(4) smoothed spectral estimates, simple and cross, for the same frequencies,

(5) rectangular and polar coordinates for, and the squared absolute value of, the complex coherence, which is representable as

$$\frac{\text{cospectrum} + (\sqrt{-1})\ \text{quadrature spectrum}}{\sqrt{\text{product of individual spectra}}}$$

In more detail, the program computed the following quantities, where x_i and y_i, $i = 1, 2, \ldots, N$ are corresponding values of the two series φ

(1) Sums of values and of cross-products used in later expressions,

(2) Sums of cross-products adjusted for observed means:

$$(\text{Term 1})_p = \sum_{i=1}^{N-p} x_i \cdot y_{i+p} - \frac{1}{N-p} \sum_{1+p}^{N} y_i \sum_{1}^{N-p} x_i$$

$$(\text{Term 2})_p = \sum_{i=1}^{N-p} y_i\, x_{i+p} - \frac{1}{N-p} \sum_{1+p}^{N} x_i \sum_{1}^{N-p} y_i$$

and estimated covariances, auto and cross, for lags p from 0 to m:

$$(QX)_p = \frac{1}{N-p} \left(\sum_{1}^{N-p} x_i x_{i+p} - \frac{1}{N-p} \sum_{1+p}^{N} x_i \sum_{1}^{N-p} x_i \right)$$

$$(QY)_p = \frac{1}{N-p} \left(\sum_{1}^{N-p} y_i y_{i+p} - \frac{1}{N-p} \sum_{1+p}^{N} y_i \sum_{1}^{N-p} y_i \right)$$

$$(QC)_p = \frac{1}{2(N-p)} \left((\text{Term 1})_p + (\text{Term 2})_p \right)$$

$$(QQ)_p = \frac{1}{2(N-p)} \left((\text{Term 1})_p - (\text{Term 2})_p \right)$$

(3) Raw spectral estimates

$$(LZ)_h = \frac{1}{m} (QZ)_0 + \frac{2}{m} \sum_{1}^{m-1} (QZ)_p \cos \frac{\pi ph}{m} + \frac{1}{m} (QZ)_m \cos \pi h$$

where Z may be X, Y, C or Q and both h and p run between 0 and m

(4) Smoothed spectral estimates

$$(UZ)_h = 0.23(UZ)_{h-1} + 0.54(UZ)_h + 0.23(UZ)_{h+1}$$

where $0 \leq h \leq m$, Z = X, Y, C or Q and

$$(LZ)_{-1} = \begin{cases} (LZ)_1, & Z = X, Y \text{ or } C \\ -(LQ)_1, & Z = Q \end{cases}$$

$$(LZ)_{m+1} = \begin{cases} (LZ)_{m-1}, & Z = X, Y \text{ or } C \\ -(LQ)_{m-1}, & Z = Q \end{cases}$$

(The use of coefficients 0.25, 0.50, 0.25 in place of 0.23, 0.54, 0.23 would have been more satisfactory.)

(5) Rectangular and polar coordinates CX, CY, θ, and R of the complex coherence

$$(CX)_h + i(CY)_h = R_h e^{\sqrt{-1}\,\theta_h} = (QC)_h + \sqrt{-1}\ (QQ)_h$$

and the square of its modulus, R^2, also called the coefficient of coherence.

In this particular program, m could be given any value up to 200.

1.D2 Precautions to avoid zero frequencies

The program itself includes protection against non-zeroness of the overall mean of the data. In some circumstances this would suffice. Since we are concerned with avoiding any unnecessary doubts, we wished to add a long string of zeroes before, and another long string after, the actual data.

If this were to be done incautiously, the actual data would almost surely have a mean which is not precisely zero. By sandwiching the data between two strings of zeroes, we would then introduce (possibly in a concealed way) a step at the beginning of the data and another step at the end. The fact that the end values of the actual data are not equal to the mean introduces further breaks.

To avoid this difficulty, the 50 end values (20 for the shorter records) were multiplied by

$$\frac{1}{2}\ (1 + \cos(\pi - \frac{i\pi}{50}))$$

which smooths out such a break quite effectively. (See Annex B, sections 1.B2 to 1.B4, for more details on the use of "cosine tapers".)

1.D3 Choice of frequency limit and smoothing

The initial analyses, whose results were shown in Section 1.6, were frankly exploratory in nature. The upper frequency limit of 100 millicps was not based upon specific knowledge of the likely danger frequency for microseisms. Instead, initial inquiries were based on the joint spectral analysis of "Palisades I" with "Waynesburg I". Probably the most illuminating result is the plot of smoothed values of the complex cross spectrum, i.e. of

$$\text{cospectrum} + (\sqrt{-1})\ \text{quadrature spectrum}$$

as a function of frequency. This is shown as Figure HG. The cross spectrum is small for small frequencies, but from 25 millicycles onward is substantial. The important and noteworthy aspect of this chart is the steady progression of phase between 20 and 90 millicps. Beyond 90 millicps the behavior of the phase is more irregular. This suggested confining attention, initially, to the region well below 80 or 90 millicps.

The choice of a method of "eliminating", i.e. greatly reducing, the contributions from frequencies above 90 millicps was mainly controlled by pressure of circumstances. Smoothing by 5's and by 3's, as shown in Section 1.B5, removes

frequencies above 90-95 millicps quite effectively, and could be carried out manually quite easily. Several sorts of additional or alternative smoothing were tried, but none of them seemd to lead to improvement.

The actual computations involved finding moving sums of cross-products

$$h(\tau) = \sum f(t-\tau)g(t)$$

and then smoothing these by 3's and 5's. This is arithmetically equivalent to first smoothing the Waynesburg I trace by 3's and 5's, and then using this smoothed trace to form moving sums of cross-products.

There are clearly good reasons for further inquiry into (i) the usefulness of frequencies just above 100 millicps, and (ii) the usefulness of better pulse shaping.

1.D4 Follow-up

It is natural to fear that the clarity of the results obtained for the sense of the initial Rayleigh wave was not due to the moderately sophisticated method of analysis used --- that we might have been able to spot senses as easily from the raw seismograph tracings. Figure J reproduces, at 2-to-1 enlargement, the relevant portions of the Palisades I, II, III and IV seismograph traces. The eye of a statistician unused to seismograph tracings sees little in the first two traces, and nothing in the last two, that could be used to judge sign.

Further evidence is offered by the plot, given as Figure K, of the smoothed (by 3's and 5's), Waynesburg record. The length of the corresponding moving linear combination is very substantial. Thus it is not surprising that concealed facts are revealed.

The partial similarity between Waynesburg I, after smoothing, and the results of applying it as a moving linear combination is so far unexplained. It is natural to be suspicious that, perhaps, smoothing alone is accounting for more than we realize. Figure L shows Palisades III, smoothed by 3's and 5's. Again we fail to see a distinctive signature. Presumably the use of moving cross-correlation is essential to the success obtained.

1.D5 Individual spectra

Estimates of smoothed average spectral density (dimensions mm^2 per cps) of the individual records are a by-product of the program used to obtain moving cross-correlations. Figures M, N, P, Q, and R show the estimates on a logarithmic scale for Waynesburg I and Palisades I, II, III and IV respectively.

When we compare these figures, and especially when we examine Figure R, we see that above a frequency of about 160 millicps we have a flattened spectrum which is probably not due to the shocks we are studying (since it is most noticeable for Palisades IV, the weakest shock). We have rather arbitrarily called this frequency range "microseisms (?)" and have denoted estimates above 160 millicps by "x". In the case of Waynesburg I and Palisades I the signal from the shock is strong enough to dominate the microseisms for 10-30 millicps beyond 160 millicps, so far as the spectrum goes.

At the opposite, low frequency, side a peak at "zero frequency" falls off steeply for 5-20 millicps. Careful consideration shows that this is probably not leakage of very low frequencies through the digital filter, contrary to the natural first guess. So far no particular interpretation has been assigned to this part of the spectrum. (The unusual height at zero frequency of the Palisades II spectrum is probably due to the omission of cosine tapers in this instance.)

With the exception of the very weak spectrum from Palisades IV, the remainder of the spectrum, from 5-20 millicps to 160-190 millicps, shows a first generally rising, then falling trend. In every case (except Palisades IV), attempts to draw a smooth peak run into difficulty with a group of low estimates just where the peak should fall. (These estimates have been indicated by filled circles.) What this "hole in the head" phenomenon means is quite unclear. No reasonable explanation of it as an artefact has been discovered.

In the case of Palisades I, the initial rise toward the peak is unusually steep, and appears smoother. No explanation available.

Having examined the spectra before smoothing, it is also of interest to see what they look like after smoothing. Figure S shows the spectrum, not of a smoothed record, but of the result of smoothing the moving cross-products between Waynesburg I and Palisades I. Thus it is, approximately, the square of the effective spectrum. It shows very definite character, for which there is, as yet, no explanation.

1.D6 Phase relations

As mentioned above, cross-spectra with a pseudo-record give rise to overall phase information, provided the source was an impulse. Before tackling the analysis of such results seriously, it would be well to work up the relative phases of Waynesburg I and Palisades I, as shown by their cross-spectra.

We are concerned with relative phases, and have used arbitrarily different time origins at the two sites. Consequently we are free to alter observed phase angles by an arbitrary linear function of frequency. We should obviously choose this linear function, which amounts to re-choosing the arbitrary difference of time origins, so that the results are as simple as possible.

Figure T shows the results of one such choice. In constructing it, one is vigorously reminded that individual phase angles are only determined to plus or minus an integer multiple of 2π at three points

(1) below 10 millicps,

(2) near 110 millicps,

(3) above 225 millicps,

where it is not clear how best to choose the additive $\pm 2k\pi$. If we had phases for 5-10 pairs of records for similar shocks, we might well be able to trace phases confidently across some or all of these regions. With this one pair we cannot.

The region below 20 cps corresponds to the "decline from zero frequency" in the Palisades I spectrum. Phasewise it represents either (i) a "bump" of amplitude about 180°, or (ii) a steady slant amounting to -360°.

The uncertainty at about 110 millicps corresponds to the upper frequency limit for the "hole in the head" phenomenon. The lower frequency limit of this phenomenon corresponds to a phase jump near 90 millicps which was interpreted as a jump up and back. Perhaps we should be more doubtful here.

The region above 225 millicps is deep into microseisms, and probably troubled by folding. It is not surprising that phases should be irregular and dubious here.

What remains? A region of linear phase, chosen to be horizontal in the figure, from 20 to 80 millicps. A second region of linear phase, gently slanting in the figure, from 110 to 180 millicps. Something happens near 150 millicps, where a group of points are 180° away from the line that fits on each side. What? A third region of linear phase, steeper in the picture, and not emanating from the same origin, from 180 to 225 millicps, which must presumably be microseisms. (This relatively good phase agreement presumably requires that on the date in question, the microseisms also came from the West Coast.)

Generally speaking breaks and regions are similar for spectra and phase.

Analysis of overall phase effects throws less light on the situation than does this relative phase analysis. Coherent phases can perhaps be followed from 25 to 145 millicps for Palisades I, and from 0 to 10, 40 to 130 and 190 to 225 millicps for Waynesburg I. Only the 190 to 225 millicps region is surprising. (Does this mean that this noise is not microseisms?) Detailed consideration should await the analysis of more data.

ANNEX E
to
Appendix 9

POSSIBILITIES OF IMPLEMENTATION IN PRACTICE

John W. Tukey

The discussion in this Annex has revolved around early exploration of the technique. What difficulties and what equipment requirements would have to be met in its use in a practical situation?

Fundamental to an adequate answer to this question is knowledge of how many reference traces will be required. About this we may only guess. The successful use of a Waynesburg trace as a reference for the Palisades trace from the same earthquake suggests that differences in epicentral distance up to ±500 km may be acceptable. In such a case, four or five reference traces would cover distances out to 4000–5000 km. Different sets might well be required for (i) continental paths, (ii) oceanic paths, (iii) mixed paths. A set of, say, 20 reference traces might well suffice.

One alternative would be to use a seismograph with digital output, and apply the reference traces with a computer. It would probably require a few years to develop the techniques and equipment (including digitally recording seismometers) required to make such a system feasible in an extensive field program. And after such development, the results might be unduly expensive. Thus we need to consider other possibilities.

If the phase and amplitude corrections corresponding to the smoothed reference traces can be realized by analog devices, as is probably the case, the conventional analog output from the seismometer may be passed through various analog compensators and the several outputs displayed on one or two 10-pen recorders. Visual examination should then usually allow us to select not only the most nearly compensated version but also to determine, by examining the selected trace, the sense of the initial disturbance.

(While Havelock, The propagation of disturbances in dispersive media, Cambridge, 1914, page 30, illustrates a case, due to Schuster, where a pulse appears with alternate signs after traveling different distances, there seems little danger of

running into such a situation while phase-compensating earth-shocks. This is especially true when we consider the great breadth of the initial disturbance in Schuster's example,)

Realization in analog devices, of the desired characteristics at such low frequencies might be possible (i) electronically, with much aid from inverse feedback, (ii) hydraulically or pneumatically. Such realization would be aided by the fact that the needed reference traces would certainly fall into sequences, adjacent members of which would differ by rather similar steps. These incremental corrections, indeed, would tend to resemble corrections for travel over the incremental distances. Thus it would probably be simpler to make up analog versions of the incremental corrections rather than of the over-all corrections; and to tap pen recordings from various points along a chain of incremental corrections.

It is worth noting that such an analog system could be simulated on a digital computer, so that the usefulness of such multipen records could be determined without building up the analog system.

FIGURE A
Three-octave pulses

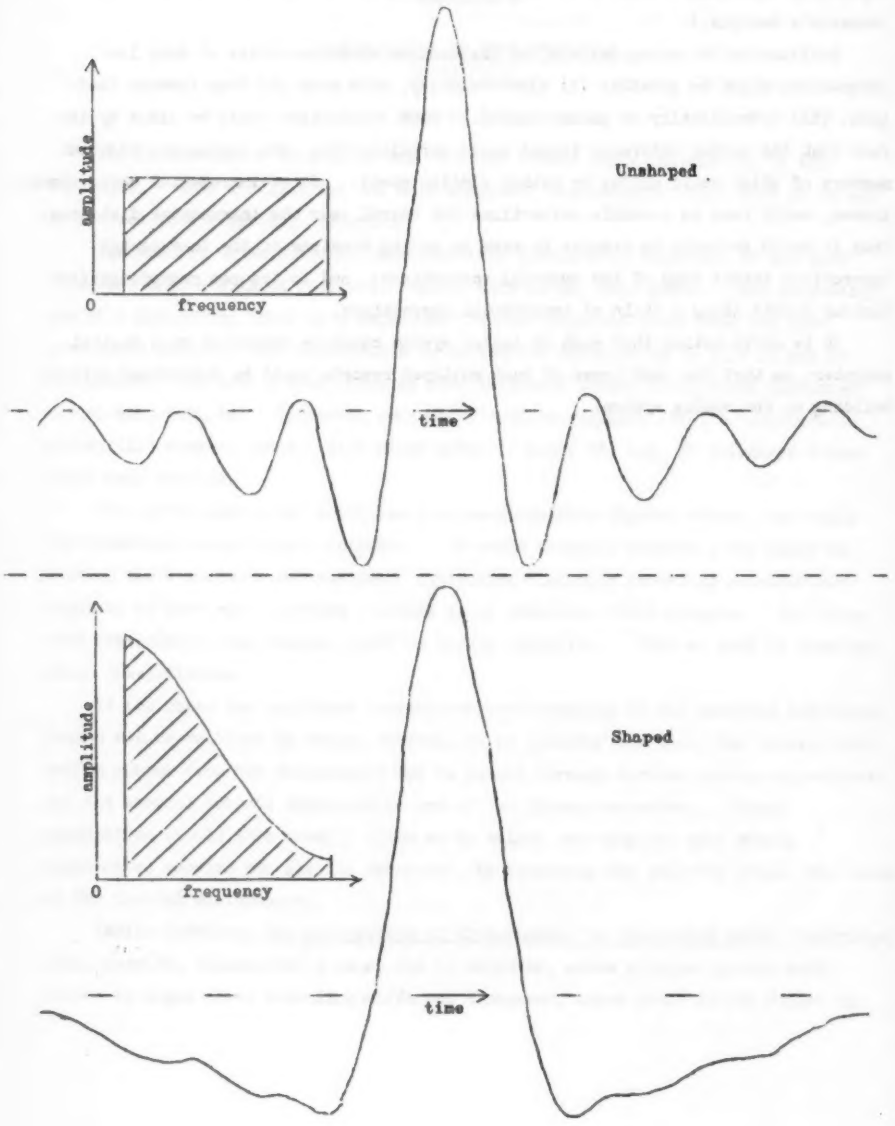


FIGURE B

Two-octave pulses

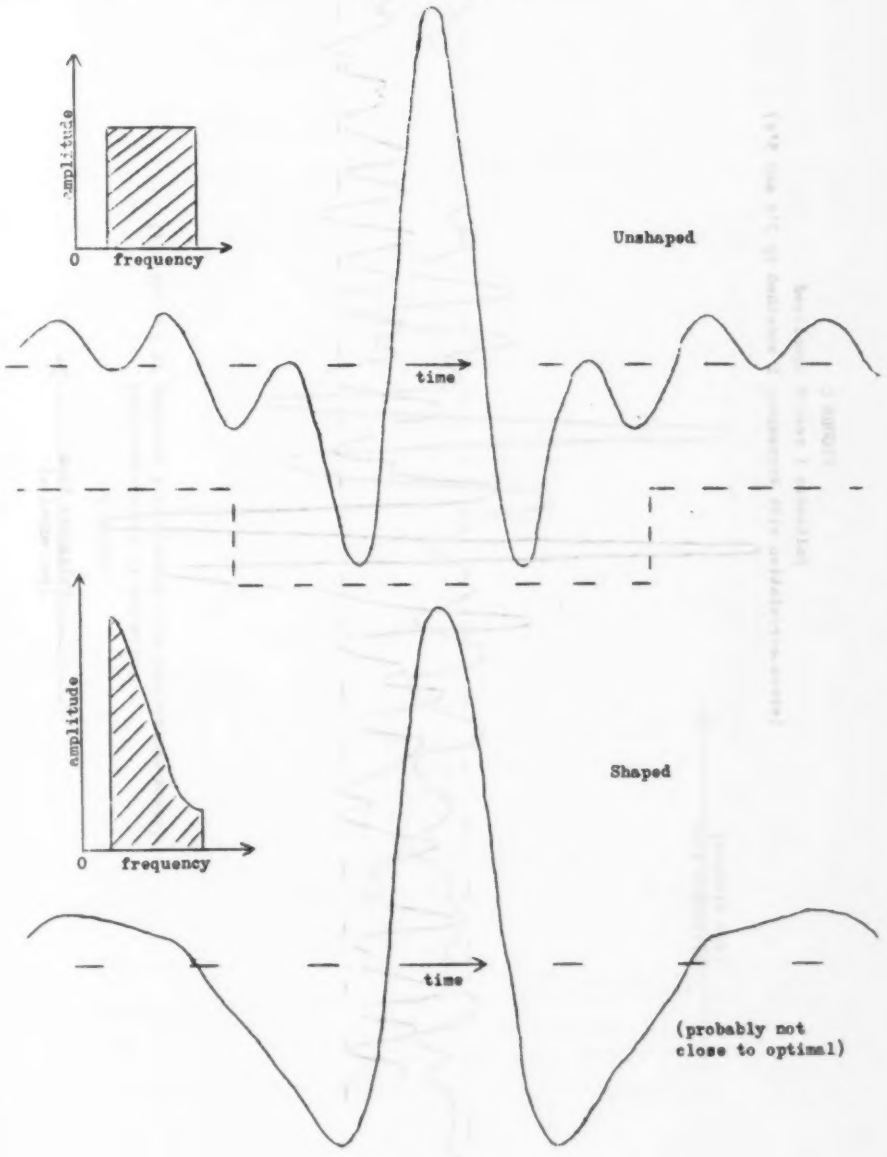


FIGURE C
Palisades I record equalised
(cross-correlation with Waynesburg I smoothed by 3's and 5's)

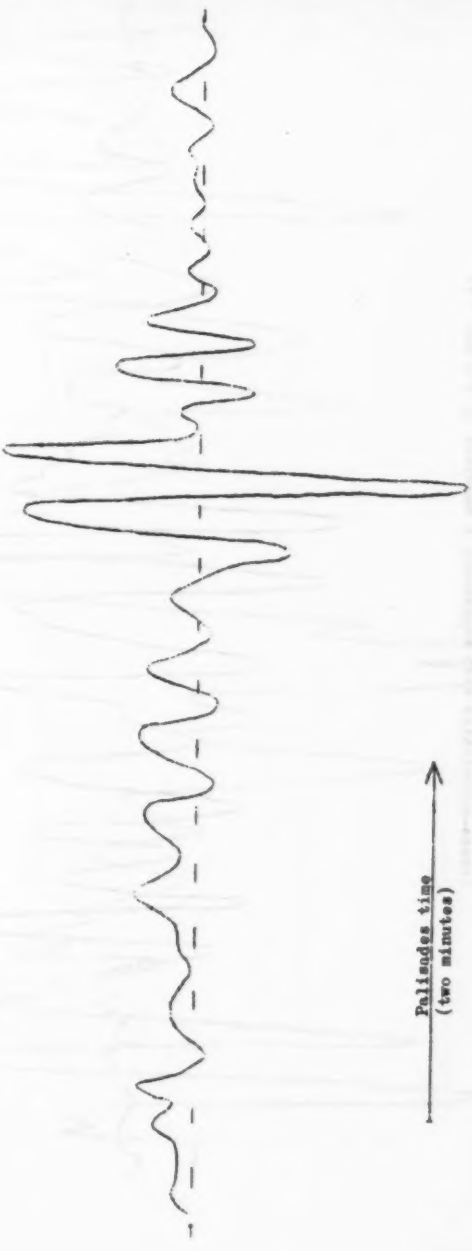


FIGURE D
Palisades II record equalized
(cross-correlation with Waynesburg I smoothed by 3's and 5's)

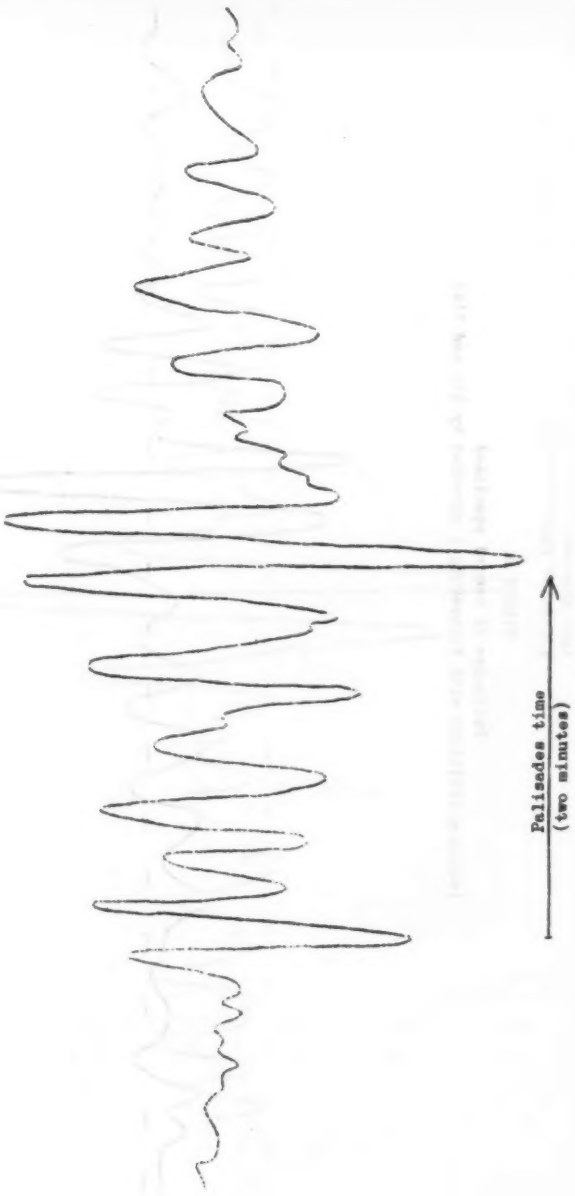


FIGURE E
Palisades III record equalized
(cross-correlation with Waynesburg I smoothed by 3's and 5's)

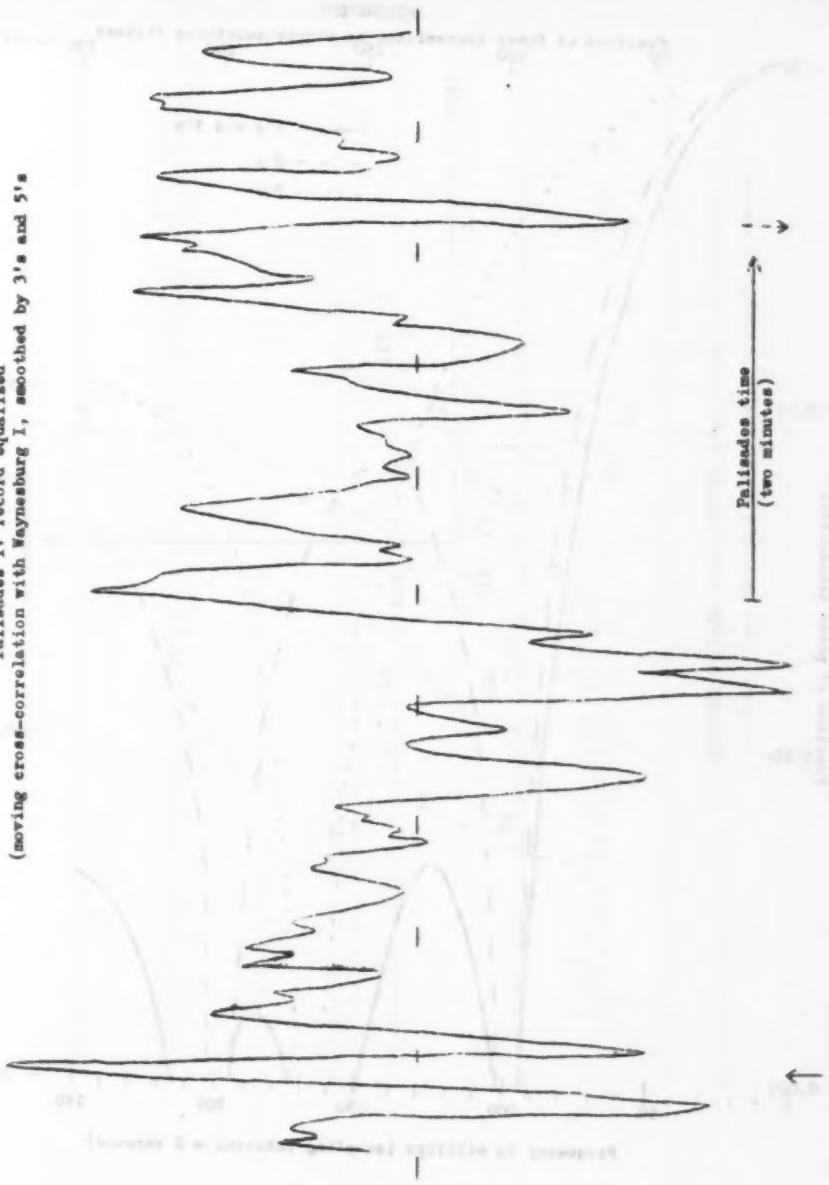


FIGURE F
Palisades IV record equalised
(moving cross-correlation with Waynesburg I, smoothed by 3's and 5's

FIGURE G

Fraction of Power transmitted by simple smoothing fitters

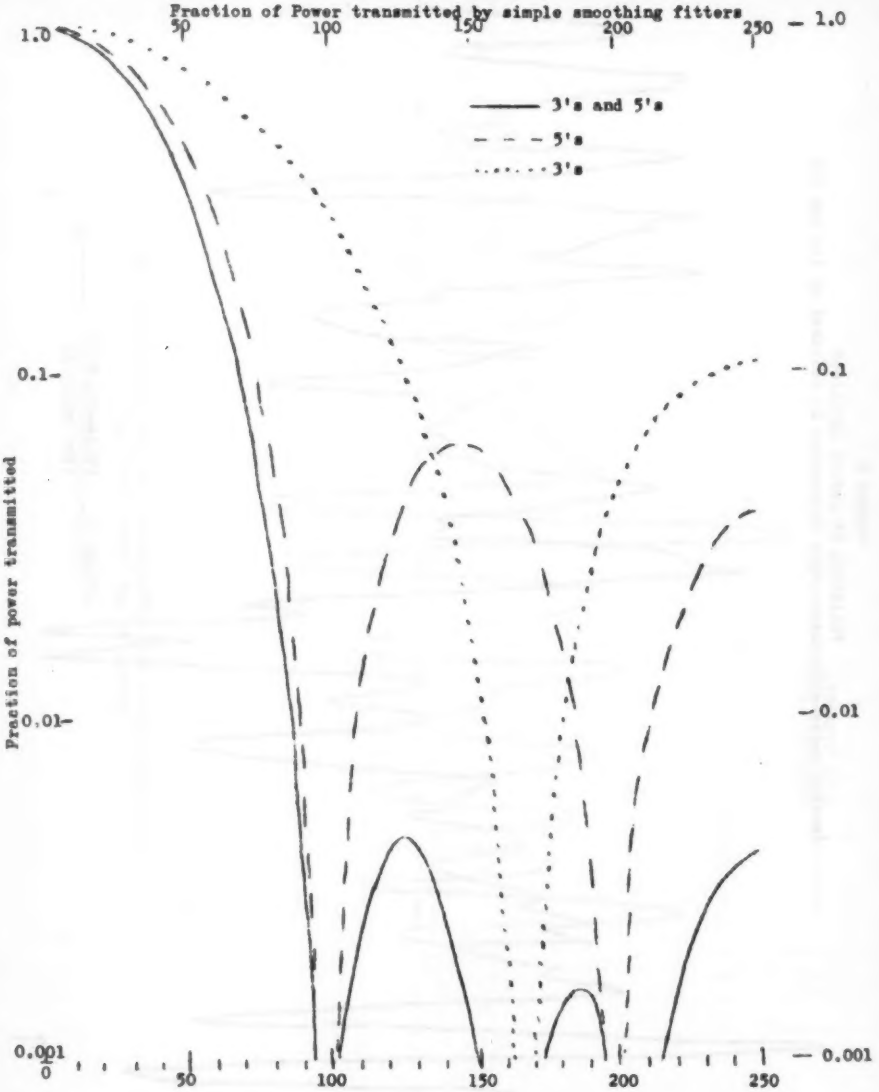
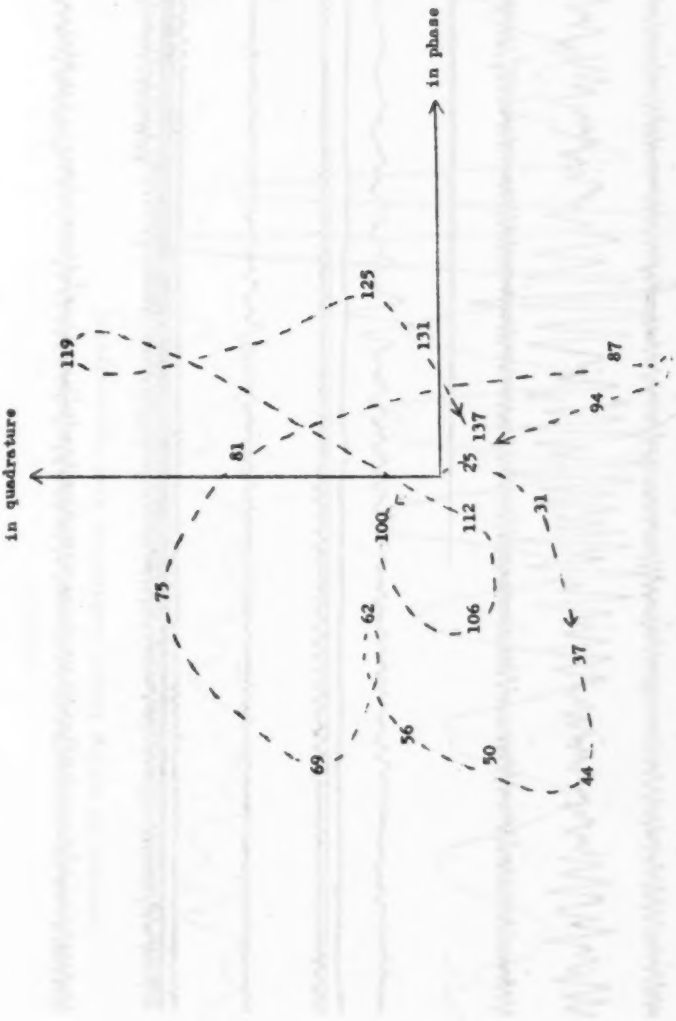


FIGURE H



SMOOTHED COMPLEX CROSS-SPECTRA (Waynesburg I vs Palisades I)

(Numbers along curve are frequences in millicycles/second)

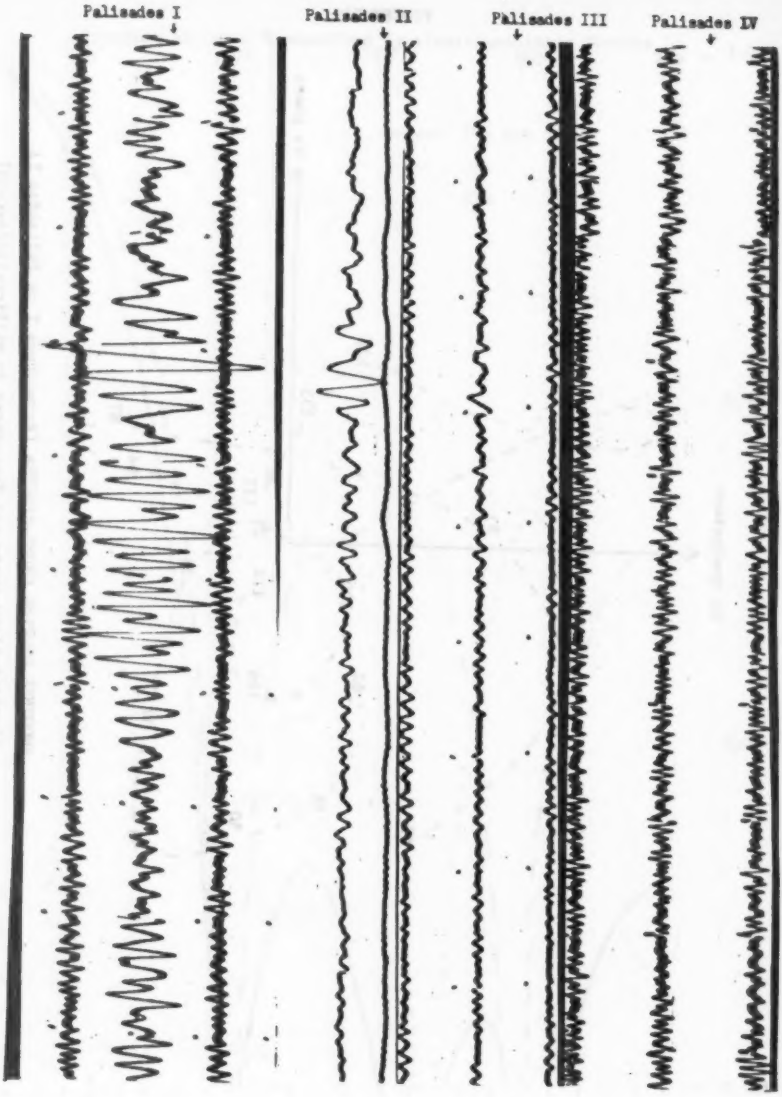


FIGURE J
2-to-1 enlargements of original seismometer traces

FIGURE K
Waynesburg I record smoothed by 3's and 5's
(reverse of moving linear combination used for analysis)

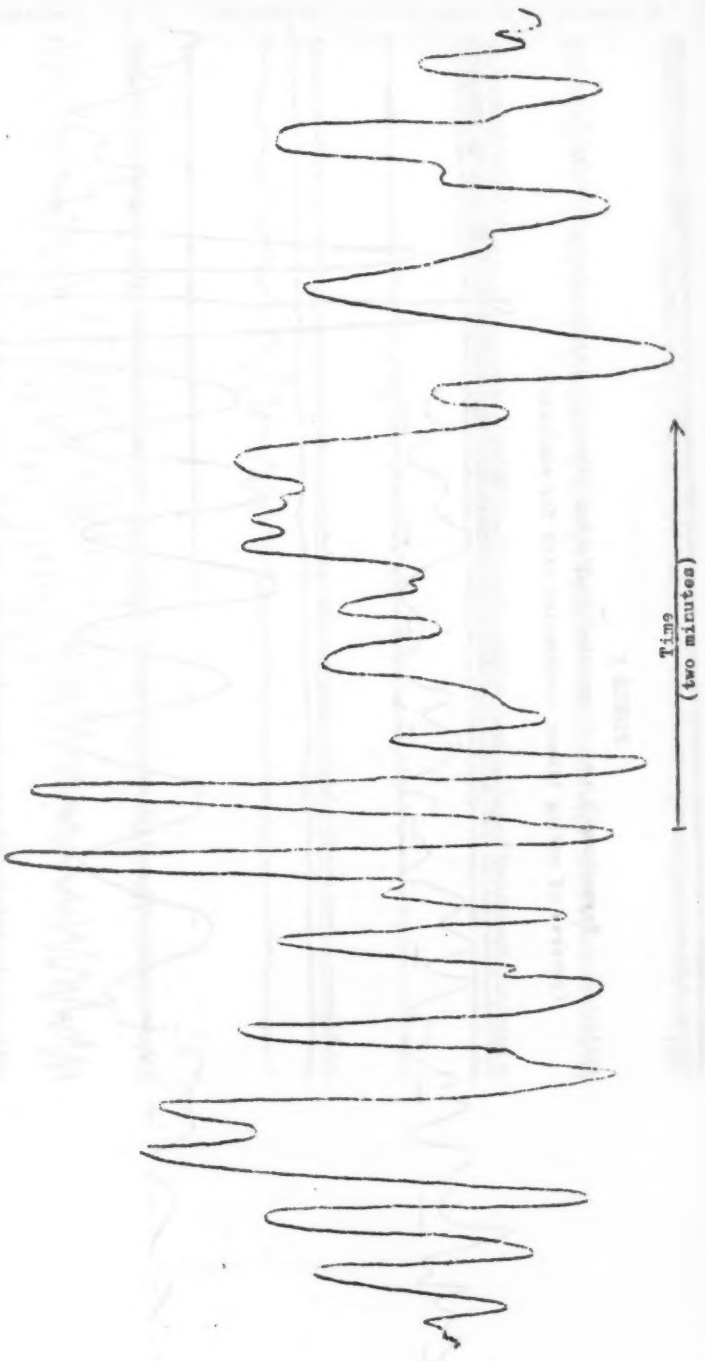


FIGURE L

Palisades III Record smoothed by 3's and 5's

FIGURE M

Spectrum of Waynesburg I
(logarithmic scale)

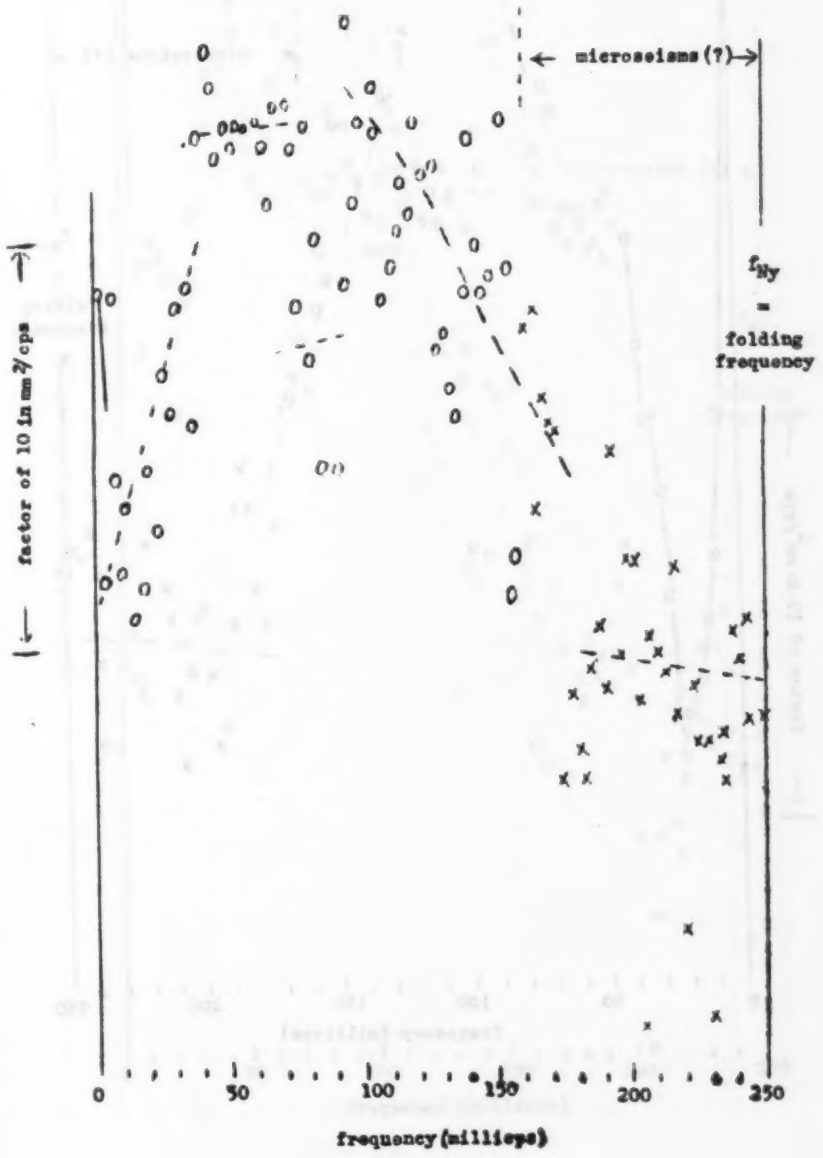


FIGURE N

Spectrum of Palisades I
(logarithmic scale)

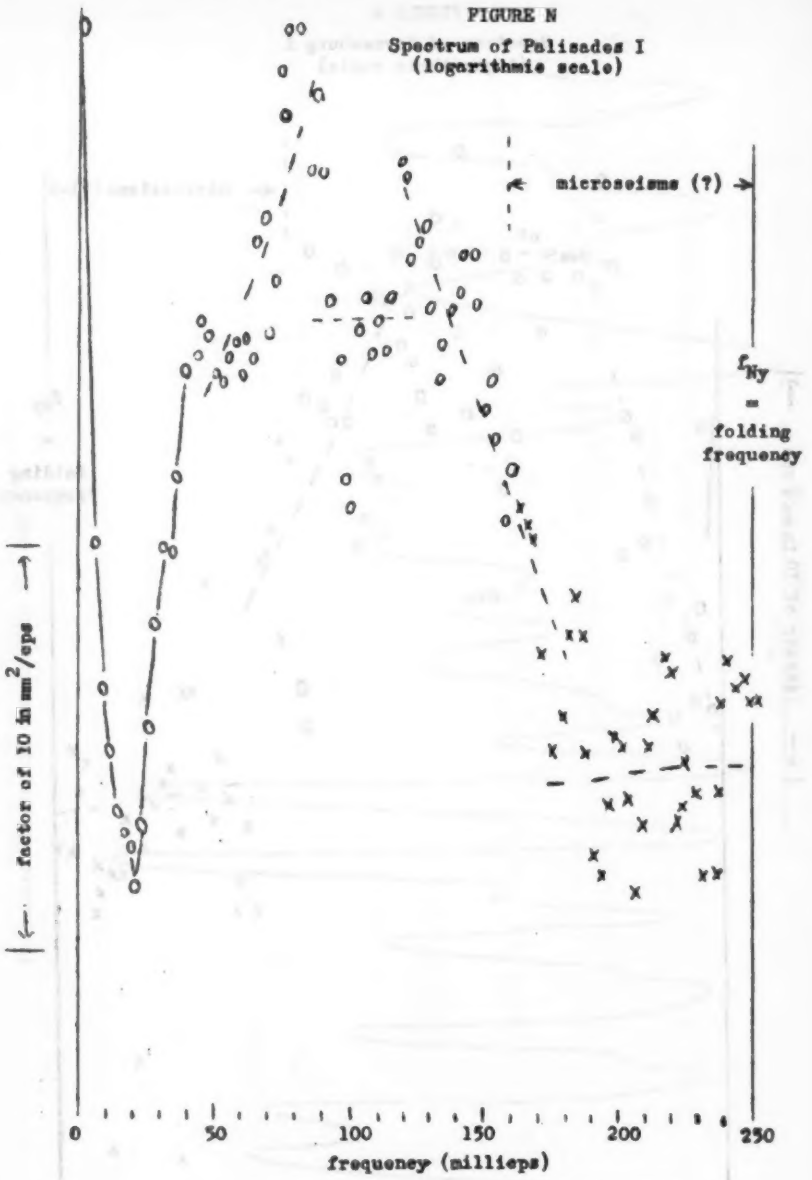


FIGURE P

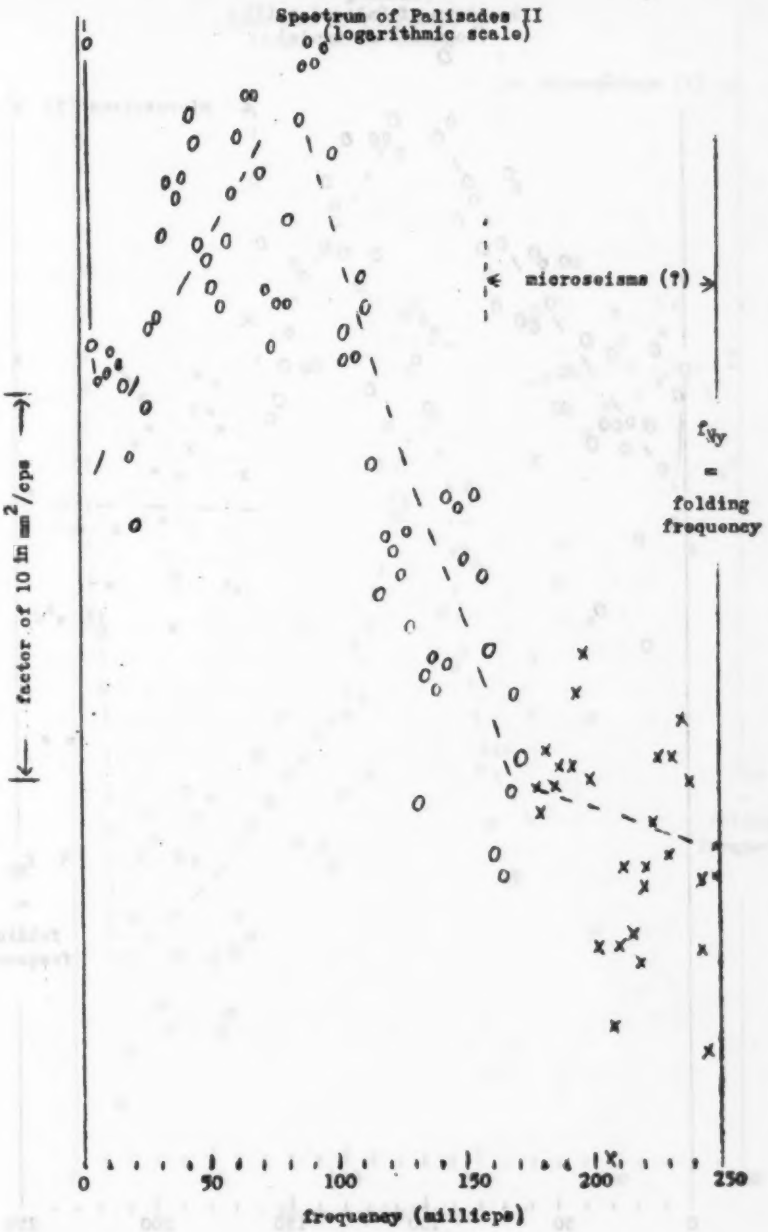

Spectrum of Palisades II
(logarithmic scale)
microseisms (?)
f_{Ny}
=
folding
frequency
factor of 10 in mm^2/cps
0
50
100
150
200
250
frequency (millicps)

FIGURE 9
Spectrum of Palisades III
(logarithmic scale)

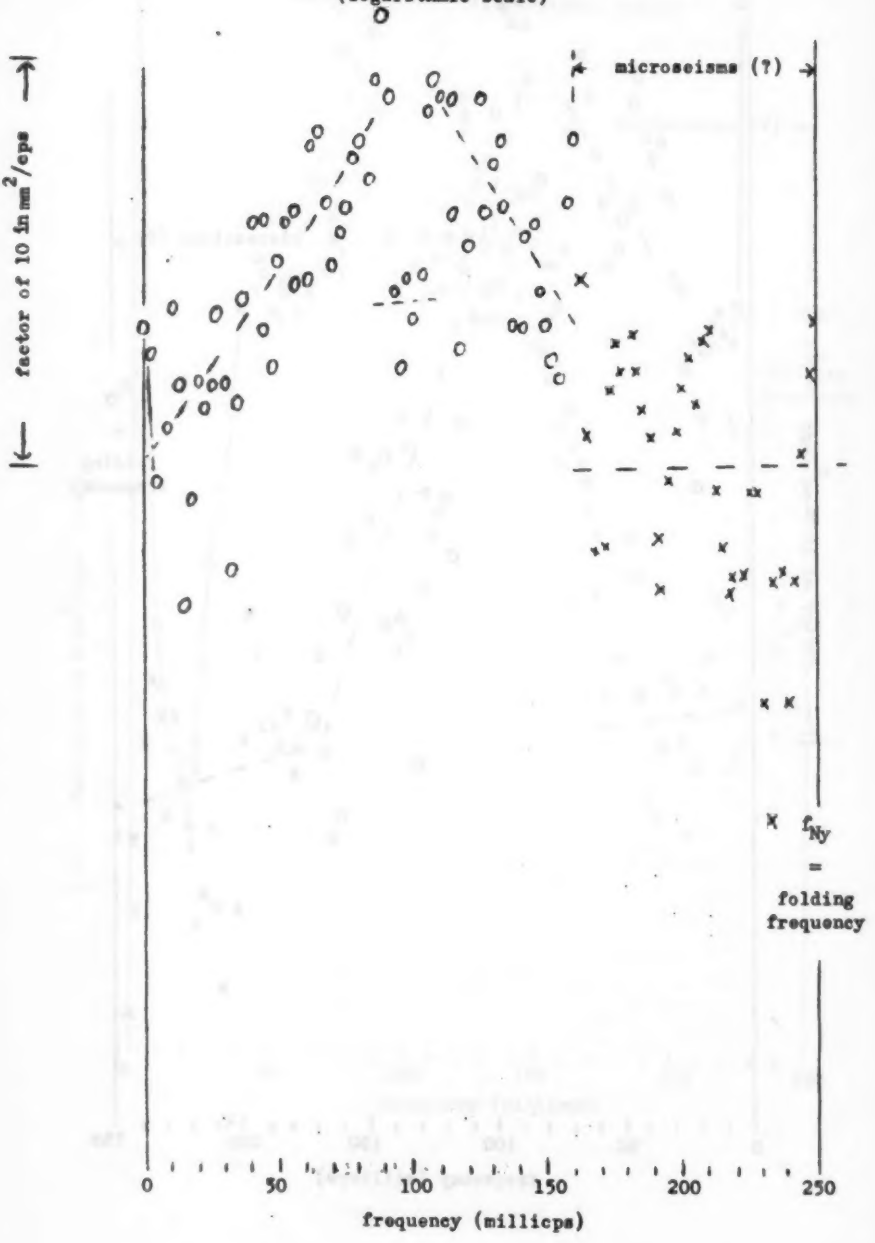
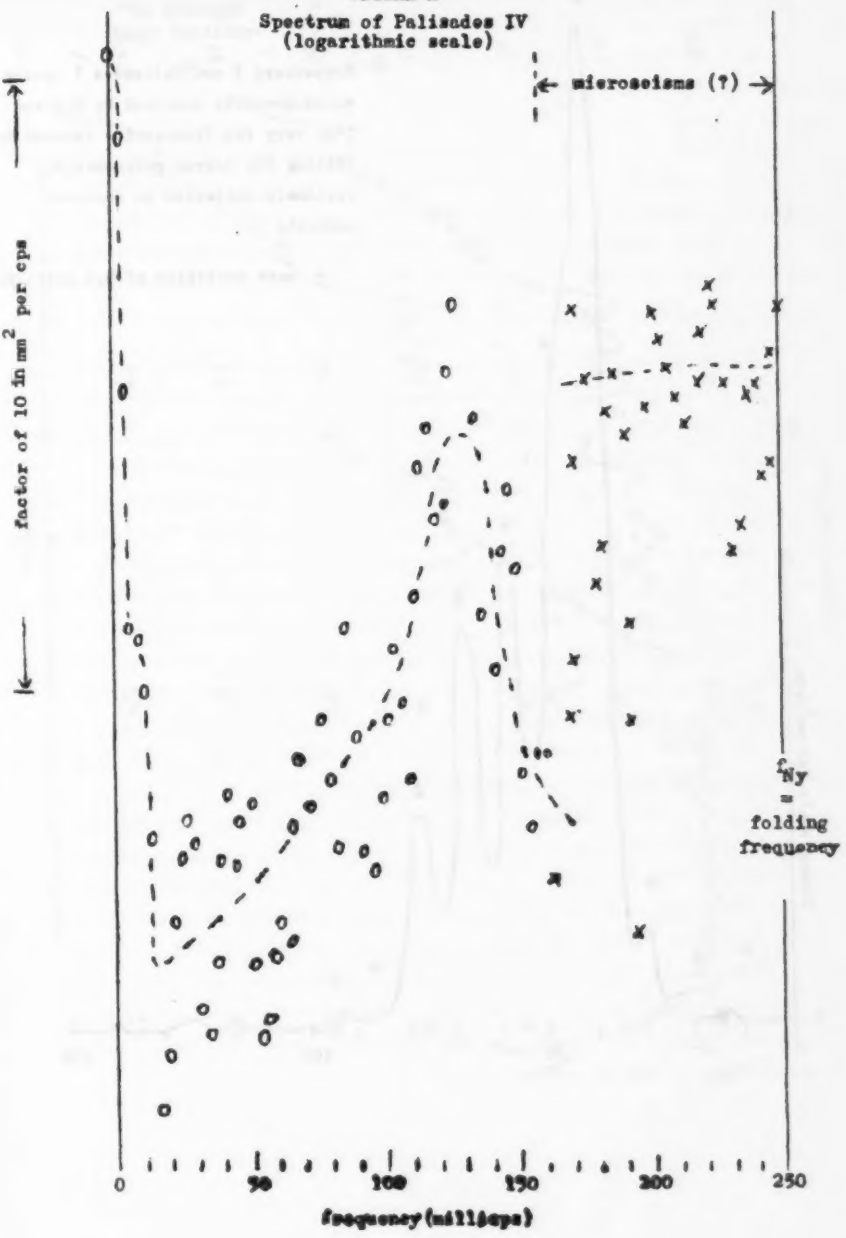
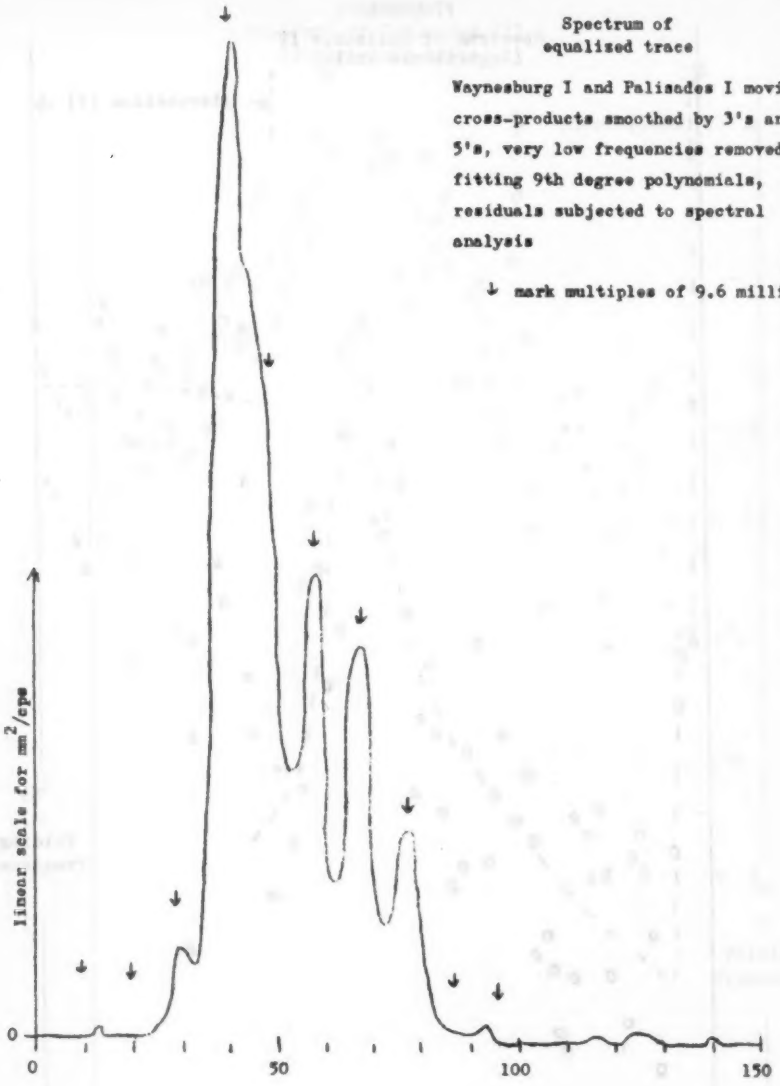


FIGURE R


Spectrum of Palisades IV
(logarithmic scale)
← microseisms (?) →
factor of 10 in mm² per cps
f_Ny = folding frequency
0
50
100
150
200
250
frequency (millicps)


Spectrum of
equalized trace
Waynesburg I and Palisades I moving
cross-products smoothed by 3's and
5's, very low frequencies removed by
fitting 9th degree polynomials,
residuals subjected to spectral
analysis
↓ mark multiples of 9.6 millicps
linear scale for mm²/cps
0
0
50
100
150

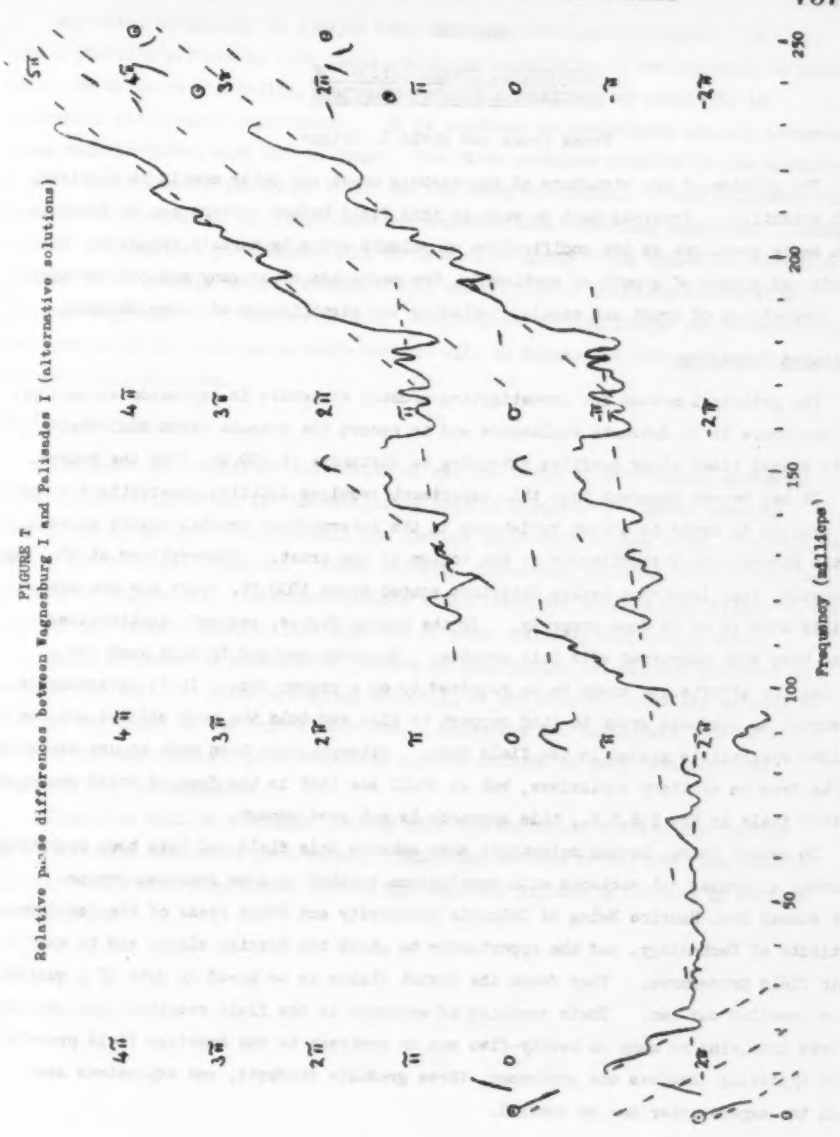

Relative phase differences between Wagnesburg I and Palisades I (alternative solutions)
Frequency (millicps)
4π
3π
2π
π
0
-π
-2π
50
100
150
200
250

FIGURE T

Appendix 10

GEOPHYSICAL INVESTIGATION OF CONTINENTAL CRUSTAL STRUCTURE

Frank Press and David T. Griggs

The problem of the structure of the earth's crust and outer mantle is receiving much attention. Progress must be made in this field before answers can be found to such basic questions as the modification of seismic waves by earth's structure, the origin and manner of growth of continents, the mechanism of orogeny and compensation, the composition of crust and mantle, including the significance of phase changes.

Explosion Seismology

The principal method for investigating crustal structure is explosion seismology. The procedure is to detonate explosions and to record the seismic waves and obtain their travel times along profiles extending to distances of 400 km. from the source.

It has become apparent that this experiment requires detailed observations along the profile in order to detect variations in the intermediate crustal layers as well as the Mohorovicic-discontinuity at the bottom of the crust. Observations at 10-15 km intervals, each involving twelve detectors spaced about 1000 ft. apart are now needed if this work is to be done properly. In the United States, academic institutions alone have been concerned with this problem. No group engaged in this work can marshal the efforts now known to be required to do a proper job. It is unreasonable to expect an academic group to find support to hire and hold the many skilled and semi-skilled specialists needed in the field work. Attempts have been made to use students and to draw on military explosives, but we shall see that in the face of rapid progress in this field in the U.S.S.R., this approach is not good enough.

In recent years, Soviet scientists have entered this field and have been reporting remarkable results, at variance with conclusions reached by some American groups. Last summer Drs. Maurice Ewing of Columbia University and Frank Press of the California Institute of Technology, had the opportunity to check the Russian claims and to examine their field procedures. They found the Soviet claims to be based on data of a quality which excelled our own. Their position of eminence in the field resulted from massive efforts involving as many as twenty-five men in contrast to the American field procedure which typically involves one professor, three graduate students, and explosions over which the experimenter has no control.

Explosion seismology is a major tool of solid earth geophysicists. If the United States's efforts in this field are to be competitive, a new approach is needed, one which draws on the skills, the instrumentation and manpower available in commercial geophysical exploration. It is proposed to investigate crustal structure along many profiles, each 400 km long. The first profiles would be in the vicinity of the Sierra Nevada, the Great Basin and the Rocky Mountains. Field equipment will include twelve-channel oscillographic and magnetic tape recording apparatus. Groups of four seismometers per channel will be used, each group being spaced at intervals of 1000 ft. Overall channel response will extend down to 2 cycles/second with variable high and low frequency cutoff. Explosions will be loaded and detonated by the contractor and continuous radio contact will be maintained between the shot point and recording position.

Surface Wave Methods

The phase and amplitude distortion of surface waves by the crustal waveguide offers a powerful method for investigating crustal structure. Group velocity dispersion of surface waves reveals the average properties of the crust over regions having continental dimension. Phase velocity dispersion reflects local variations in crustal thickness. Detection methods which transform surface wave trains to the initial near-source impulse also make use of phase velocity dispersion data.

It is proposed to establish a network of long period seismograph stations to analyze the data for phase and group velocity, to use Fourier transform methods to recover the shape of the initial impulse. Explosive and earthquake sources will be used and modern high speed computing machine methods of data reduction and analysis will be exploited.

This work will be performed jointly with the explosion studies and the two methods should supplement each other. Explosion methods reveal the fine details of crustal structure variation whereas the regional picture is derived by surface wave methods.

Appendix 11

OCEAN BOTTOM SEISMOGRAPHS

Jack Oliver

1. One of the most significant experiments open to the field of seismology is the determination of the seismic motion of the floor of the ocean. Virtually nothing is known about this subject although the experiment is quite feasible from a technical standpoint, and would not require an unreasonable financial outlay.

Information on the following subjects would be obtained:

1.1 Seismic Noise Level

It is difficult to speculate on the level of seismic noise on the ocean floor. On one hand, it would seem that the level would be low because of remoteness from civilization and from natural noise sources such as wind, running water, etc. On the other hand, some partially accepted theories of microseism generation require a pressure variation of the ocean floor from wave motion at the surface of the water. The writer's guess is that while the bottom may be noisy, at least in certain parts of the frequency spectrum, when there is a meteorological storm nearby, there is a good chance that a very low noise level will be encountered a large part of the time. The noise level may also vary with the geographical location, e.g., there may be periods of extreme quiet in the Arctic Ocean.

Dr. Walter Munk, who has conducted measurements of long period noise in relatively shallow portions of the oceans, has commented as follows: "Measurements of pressure on the sea bottom indicate that for a seismogram at oceanic depth the noise spectrum should be low in the frequency range 20 to 40 millicycles per second. At higher frequencies some second-order effects of sea-waves might be expected to raise the background; at lower frequencies certain resonance coupling with topography (in the shallow ocean) is known to produce a background rising sharply with decreasing frequency. Thus it might be advisable to exploit this 'gap' near 30 mc/sec. in deep ocean seismometry."

1.2 Body Waves

In addition to the effect of the noise level, whatever it may be, the recording of the body wave may be affected in the following ways. P-waves, at least the higher frequency components, should appear primarily on the vertical

component seismometer, S-waves on the horizontal. Except for a decrease in amplitude and an indication of a surface reflection, the higher frequencies should be little affected by the distant water surface, the surface may be important for the lower frequencies.

One interesting possibility is the use of a sea mount as an "exponential horn".

1.3 Surface Waves

Seismologists are certain that the surface waves, at least those corresponding to certain parts of the spectrum, undergo strong effects at continental margins, and other crustal discontinuities. Thus, it is highly desirable to obtain records of surface waves in the deep ocean basin. Outstanding questions include the nature of the 5-15 second waves propagating across oceanic paths, and the lack of short period waves of the fundamental Rayleigh mode.

1.4 Wave Guides

The near surface wave guide of the oceanic crust is understood grossly, but important details remain to be explored. For example, the low shear velocity of the sedimentary layers suggests an efficient wave guide in this layer for waves of short length, if attenuation is not too large. Some theoretical computations on this subject have already been completed; no experimental data are available.

Earthquakes occurring beneath the ocean bottom or beneath the surface of the land coastal areas frequently generate a propagating disturbance called the T phase. This phase consists of high frequency (1 cycle per second or more) waves which travel primarily through the deep ocean. Since the sources are usually deep and frequently inland, it is likely that energy radiated from the source as P or S waves is converted to underwater sound in the vicinity of the continental margin, possibly best in regions of steep submarine slopes. One study of T phases recorded at Bermuda showed that these waves could be generated by P-waves from South American shocks which strike the steep slope of the Puerto Rico deep after having traveled as much as 50 degrees of land path.

This evidence, plus the fact that underwater sound propagation is more efficient than propagation of elastic waves in the earth, suggests that ocean stations equipped to record the T phase might prove to be valuable detectors of earthquakes in coastal regions. The possibility of obtaining first motion data by this method is worth

investigating but on sheer speculation does not appear too promising.

1.5 Microseisms

The problems associated with microseisms have withstood years of study by seismologists. It may well be that the ocean bottom seismometer is the only tool that can provide the answers.

1.6 Low Frequency Sound Propagation

Conventional detectors of underwater sound are inefficient at very low frequencies. The ocean bottom seismograph will overcome this deficiency.

2. Instrumentation

Three general classes of instruments have been considered: (1) Those with the seismometer on the ocean bottom connected to the recorder on shore through a submarine cable. (2) Those with the entire seismograph on the bottom, recording for periods of weeks or months. The entire instrument could be summoned to the surface by the retrieving ship for service. (3) Seismometers on the ocean bottom capable of telemetering data acoustically to a ship in the vicinity.

An instrument corresponding to (2) was under construction and about three-quarters finished at the Lamont Geological Observatory when funds were cut off. This instrument was essentially a one-second seismograph of the Willmore type.

As with land-based instruments, seismometers with a variety of free periods would be desirable, at least until a suitable broad-band instrument is developed. A three-component system should be planned although a simple single component instrument would provide much valuable information.

Arrays are quite feasible, especially in the broad flat areas of the ocean, the abyssal plains, and the flat bottomed troughs.

Appendix 12

SUGGESTIONS FOR STANDARDS OF NOISE, AMPLITUDE, and SPECTRUM

Hugo Benioff

Seismic noise characteristics should probably be defined in terms of ground vibratory displacement in order to conform with existing practice. If the ground particle velocity characteristics are also desirable, they can be easily derived from the displacements.

From available information, it appears that seismic noise exhibits a continuous spectrum with several superposed bright lines or narrow bands corresponding to the microseism frequencies. The continuous spectrum varies from hour to hour at any given place, and from place to place at any given time. The microseism bands also vary in amplitude and frequency with time, and in addition may exhibit marked differences in observing sites. The spectrum may also contain absorption bands related to crustal structure of the earth, but these have not as yet been reported.

For the purposes of this panel, the seismic amplitude spectrum should be measured with appropriate frequency resolution over a frequency range from about 20 millicycles/sec to 10 cycles/sec (50 to 0.1 seconds period), at a number of different sites, and for three components. The observations should extend over a sufficient time to permit determinations of average spectrum levels for minimum, average, and maximum noise conditions for each site.

Measurements of other characteristics of noise such as spatial coherence and type of distribution are also desirable - the former especially for help in predicting the effectiveness of arrays.

In order to discuss the ratio of signal to noise, it will be necessary to have measurements of the amplitude spectra in three components of the initial P waves and surface waves of earthquakes and underground blasts at different distances from the sources and at different observing sites. It may also be desirable to include measurements of the time derivative of the amplitude spectrum of these events to disclose possible identifying characteristics. Since the signal is far from Gaussian in character, other measures may prove more appropriate.

With satisfactory measurements of the noise and signal spectra, it should be possible to specify optimum acceptance bandwidths, sensitivities, and maximum allowable

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instrument noise levels for the seismographs, as well as the necessary attenuation characteristics for microseism notch filters.

When the acceptance bandwidth is known, the amplitudes of signal and noise can be determined in terms of root mean square displacement, peak displacement or average displacement. The ratio of signal to noise can be given in the same terms. It is not clear to the writer what sort of description will prove more effective for specifying the minimum ratio of signal to noise for detection and for identification.

Appendix 13

IMPROVED SEISMOGRAPHS

Hugo Benioff

Development of seismographs for improved detection and identification of earthquake and blast waves must be coordinated with information on the spectra of signals and noise not now available. For example, we do not know whether the noise spectrum approaches flatness with respect to ground particle velocity or displacement. Similarly, we do not know enough about the signal spectrum to specify the optimum bandwidths for detection and identification of either initial P-waves or surface waves. Hence, much of the following considerations must be tentative only.

1. Short Period Seismographs

On the basis of presently available information, the optimum acceptance band for the detection and identification of initial P-wave pulses is approximately from 0.4 cycles/sec. to 10 cycles/sec. (2.5 to 0.1 seconds period). The low frequency cut-off, however, has been dictated principally by the effects of the 6 sec. microseisms and the 18 db per octave slope of the short period seismographs now in use. With a sharp notch filter designed to reduce the response to 6 sec. microseisms, it may be found that a lower cut-off frequency will be preferable. Such a filter is described in the paragraphs on surface wave recorders.

In order to improve our ability to differentiate between earthquakes and blasts, it may be necessary to derive spectra of the first motions and to introduce post recording filtering and inverse transfer function equalization. This will require amplification of the seismograph response and recording on punched paper tape for analysis by digital computers. In the case of the short period recorders, this procedure may require an excessive amount of tape per instrument per day and, therefore, recording will have to be done first on magnetic tape either digitally or analogically with the provisions for daily or weekly erasure. The portion of the magnetic tape of interest can thus be transferred to appropriately punched tape for analysis. In any case, an ordinary analog recorder, preferably visible

writing, is required for monitoring. For the short period recorders, the required amplification can probably be obtained in the initial or pre-amplifier stage with galvanometer-photocell tube amplifiers of the type now available from the Geotechnical Corporation. Following this, the Geotech No. 4983A Amplifier or equivalent should be satisfactory.

Substantial improvement of signal to noise can be expected with the use of arrays of seismographs. These will not be discussed in this appendix.

Figure 1 shows a recording system with the frequency response now in use modified for magnetic tape digital and visible writing analog recording.

Figure 2 shows a similar system with the pendulum period increased to 2.5 or 3 seconds and with a notch filter inserted for the 6 second microseisms.

Figure 3 is an assembly similar to that in Figure 2 but with a displacement transducer in place of a velocity transducer operating on the pendulum.

2. Surface Wave Seismographs

Although with proper filtering of the 6 second microseisms either initially or post recording, a single recording system might be used for both the P-wave and surface wave signals, it is the writer's opinion that separate recorders for the two ranges offer distinct advantages in reliability, maintenance, and convenience. It is assumed that for surface wave detection and identification the receiving bandwidth extends from about 10 to 125 millicycles/second (100 to 8 seconds period). The high frequency cutoff (125 millicycles/sec.) is dictated by the high level of microseism energy in the 6 second period range, believed to approach if not exceed 50 db above the adjacent noise level. As in the case of the short period recorders, the surface wave instruments should include both analog and digital recording, the former preferably of the visible writing type. Since a number of different pendulum recorder combinations are possible in this frequency range, several will have to be developed and tried before the best arrangement can be chosen. It has been suggested that with digital recording and a sufficient dynamic range of the system, the 6 second microseism frequencies need not be filtered out in the recorder since they can be removed in the digital playback procedure. This imposes rather severe limitations on the recorder as to drifts arising from tilts, temperature fluctuations and other long period noise,

and in addition, makes for difficulties in effective monitoring. It is suggested, therefore, that the microseism frequencies be filtered out at least partially in the recording system. Dr. Daniel Johnson has suggested that an electro-mechanical vibrator in the form of a modified galvanometer should make an excellent notch filter. It can be tuned to the microseism frequency either manually or possibly automatically by means of a movable bridge on the suspension and it can be a relatively rugged structure. Since the recording power level for digital instruments is high relative to that used in photographic galvanometric recorders, the seismometer output must be amplified. AC amplifiers in this frequency range are generally unsatisfactory. The only DC amplifiers known by the writer to be suitable are the Liston-Becker and the Howlett-Packard. The former uses a breaker type modulator and the latter employs a photocell modulator. The breaker type is subject to wear and requires fairly frequent servicing and appears at this writing to be less satisfactory than the photocell type. It may be possible to develop a suitable galvanometer photocell tube amplifier with better operating characteristics but so far none is immediately available.

The seismometers can be provided with either velocity or displacement transducers and both should be tried on a developmental basis. With the velocity transducer the required pendulum period is longer than with a displacement transducer. The power output from the displacement transducer is higher and is in the required form for supplying a stabilising control to the pendulum against long period drift from temperature, tilt and tidal movements. The control can be effected either by direct current feedback to an auxiliary electromagnetic transducer, after proper filtering, or by actuating a servo-operated mechanical adjustment.

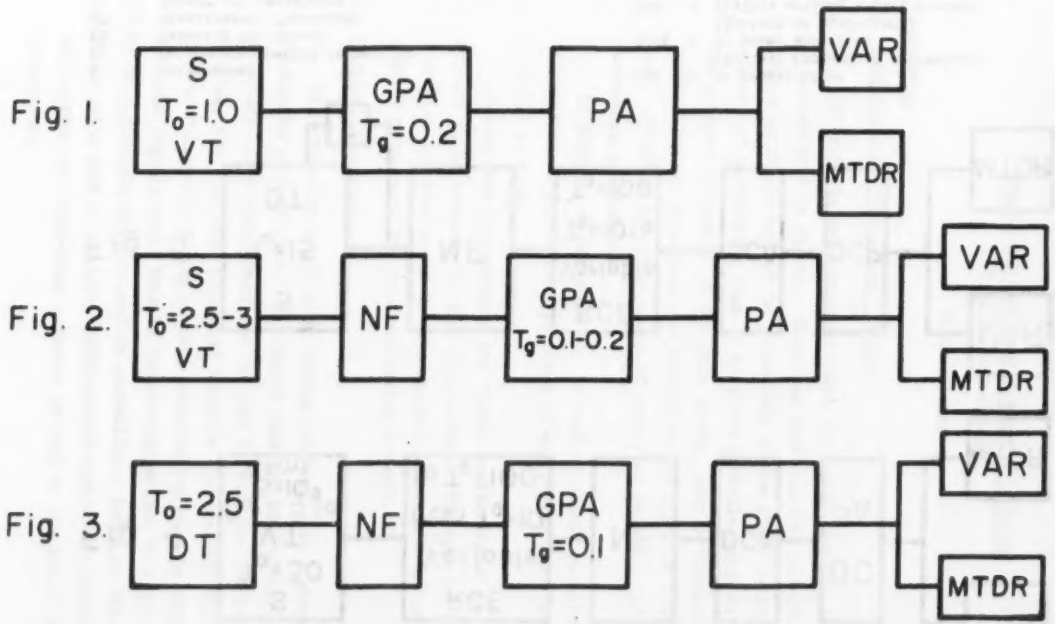
The use of long period galvanometers depends upon the success achieved with the development of a galvanometer-photocell tube amplifier since this is the only way the response of the galvanometer can be converted into amplified power. The writer has had considerable success with passive resistance capacitance networks for use in place of the galvanometers. They can be designed for exact or nearly exact equivalence to galvanometers as to frequency response characteristics of any period, although equivalence may not necessarily be required. These networks are very much more stable as to period and drift than any long period galvanometers with which the writer is familiar, even at 10 minutes period. Moreover, their characteristics can be changed at will. Without precise information as to the

noise spectrum level in this frequency range, one cannot specify the maximum permissible instrument noise level. It has been suggested to me that 1 angatrom/sec at 18 seconds may be an acceptable level.

Figures 4 and 5 are block diagrams of suggested combinations. In Figure 4 the seismometer has a free period of 30 seconds and is fitted with a velocity transducer having a winding resistance of 0.25 to 0.5 megohm for maximum output voltage. The output is fed to an RC network providing an equivalent galvanometer characteristic variable from about 15 seconds to 60 seconds. This is followed by a variable electro-mechanical notch filter for the microseisms. Amplification is provided by a Hewlett-Packard Model 425 DC amplifier or equivalent and a Geotech power amplifier or equivalent, for operation of a heated stylus analog recorder and a magnetic tape digital recorder.

Figure 5 shows a recording system with a seismometer of 15 seconds period equipped with a displacement transducer, notch filter, RC equalizing filter. Amplification and recording is carried out as in Figure 4. Since the seismometer has a displacement transducer, means are indicated for introducing a stabilizing current or servo-operated mechanical adjustment for maintaining the zero position of the pendulum. The stabilizing DC current is derived from the transducer by the use of a very long time-constant filter and is connected to an auxiliary moving coil transducer attached to the pendulum. A servo system for mechanical adjustment of the pendulum zero can be used, but is probably more complicated than necessary.

SHORT PERIOD SEISMOGRAPHS.



S = Seismometer
T_o = Period of seismometer
VT = Velocity transducer
DT = Displacement transducer
NF = Notch filter for 6 second microseisms
GPA = Galvanometer photocell tube amplifier
PA = Power amplifier
VAR = Visible writing analog recorder
MTDR = Magnetic tape digital recorder

LONG PERIOD SEISMOGRAPHS.

Fig. 4.

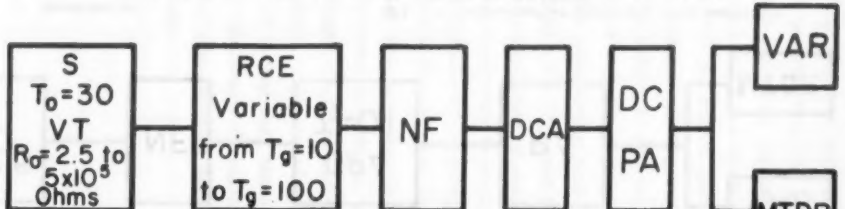
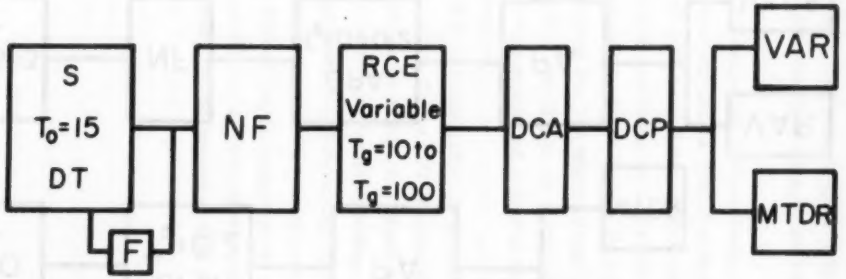


Fig. 5.



S = Seismometer
T_o = Seismometer period in seconds
VT = Velocity Transducer
DT = Displacement Transducer
R_o = Transducer resistance
RCE = Equivalent galvanometer RC filter
T_g = Equivalent galvanometer period
NF = Notch filter for microseisms
F = Filter for stabilising circuit

DCA = DC preamplifier (Hewlett Packard or equivalent)
DCPA = DC power amplifier (Geotech or equivalent)
VAR = Visible writing analog recorder (Geotech Helicorder or equivalent)
MTDR = Magnetic tape digital recorder

Appendix 14

"THROW-AWAY" OR PORTABLE SEISMIC PROBES FOR OPERATION ON LAND

John Gerrard

1. Introduction

1.1. Advantages of "Throw-Away" Units.

Aftershocks are phenomena which the Geneva network must be able to investigate in detail. Since the first-arrival seismic signals from aftershocks may not be detectable by the fixed seismic network, a means of identifying them is to place portable seismometers near the computed epicenter of the main shock. Simple "throw-away" seismic units which can be placed immediately and in quantity over a suspicious area, afford an effective means of supplying valuable information concerning aftershocks.

In general, these units may be used to obtain relatively detailed information on first-break patterns in any region where seismic activity is high.

Analog data transmission and visual monitoring of the results appears to be adequate in this application. The type of tactical operation involved would be of a special nature and not necessarily a regular process of the main monitoring network.

1.2. Tactical Deployment.

The objective would be to arrange the units in a strategic pattern in a short time. If dropped from the air, either a parachute or rotary blade arrangement may be used to slow the descent. Upon landing, the unit must establish adequate contact with the ground. If placed manually on the ground, installation must be rapid. Detected signals would then be transmitted either to a network station or to a portable station used by surveillance teams in the area. These units must be deployed sufficiently widely to provide full information on first-break patterns as well as the extent and size of aftershocks.

An excellent method of concealing a small nuclear test shot is to detonate it in the middle of a region where aftershock activity is high. In this case, throw-away probes promise greatly to simplify a very difficult detection problem, and act as a deterrent to this method of concealment.

2. Possibility of Obtaining Useful Data from the Units.

2.1. Factors Affecting Seismic Unit Performance at the Site.

The useable information transmitted from a seismic unit, which is emplaced more or less randomly, will be dependent on many environmental factors which, insofar as they are predictable, should determine design characteristics. To provide meaningful information, the seismometers must be located accurately and fixed firmly to the ground. If dropped from the air, the units may be located either by tracking the original fall and using conventional navigation methods or by using telemetry.

The unit must be designed to function adequately in as many different environmental situations as possible. The topography will determine, to a great extent, the degree of vertical positioning that can be achieved with even the most carefully designed practical packages. At some sites the topography may cause some packages to be useless. Variations in the physical state of the surface over large areas may require a choice of package types, specialized for frozen tundra, deserts, marsh lands, or rock. Even with good contact, the response of unattended seismometers will be subject to meteorological disturbances such as winds, rain, thunderstorms, and temperature changes.

However, as far as the deployment of the units is concerned, quantity might, to some extent, make up for quality.

2.2. Optimum Placement and Monitoring of Units.

The tactical deployment of these units is governed by two objectives. The first is to obtain information as to the general size and duration of aftershocks following a seismic event, and the second

to supplement the existing network in detecting first-break patterns in the area. In establishing the placement pattern, both objectives should be considered. In a region of high after-shock activity the pattern should still be broad enough for adequate information on first-break patterns originating from sources anywhere within the region. When deployed primarily for the purpose of obtaining first-motion information, the spacing should be close enough for accurate determination of the magnitudes of individual events.

The units may be monitored by planes on regular flight schedules, or via "constant-altitude" balloons used as relay stations. Continuous analog transmission should be considered for this application, since the units could be used in sufficient quantity to offset deficiencies in communication from any single unit, and probably would not work directly into the fixed network.

2.3. Data Interpretation.

Only the higher seismic frequencies will be measured with the units, primarily those contained within the first-arriving "P" group. An arrangement which seems to offer some promise is to enable the unit to receive signals from 1-10 cps with the output channeled two ways. One branch can have a 5-10 cps bandpass filter, and the other will be unfiltered. The two outputs would be transmitted to the receiving station. The unfiltered output can be analyzed and possibly correlated with other units to obtain knowledge of the nature and extent of the signal activity. The filtered output will be active only upon receiving a relatively sharp first-motion (rich in high frequencies). The two may be analyzed together in order better to separate various individual seismic events.

3. Seismic Equipment.

The seismometer employed in the units will be a ~~vertical component instrument~~ capable of delivering its own output. A variable-reluctance or moving-coil type

would be suitable. It should have maximum response in the frequency range from 1 to 10 cps and be a strong-motion instrument, stable, rugged, and compact.

Probably a modification of the velocity-type portable geophones currently used in field exploration would be suitable for this application.

4. Data Processing within the Unit.

4.1. Data Storage

Since these are throw-away packages, their instrumentation should be as simple as possible. Probably a small, closed-loop of tape or wire would be a suitable medium for temporary data storage. This sort of device would consume a minimum of power, and still be versatile enough to store and read out information in almost any time-interval combination considered desirable.

4.2. Continuous Transmission.

The least complicated instrumentation would be required if the unit were to transmit data continuously. Analog data from the seismometer would be telemetered directly. Three or more channels may be used to transmit all unfiltered data as well as time marks and possibly filtered information from the first break. The latter can be considered as a limited processing of the data, since much of the noise and unwanted signals can be reduced if the filter band is properly chosen. The relatively fast rise of the first "P" break would be the only signal able to excite it.

There does not seem to be any need for digitization in this unit since, in general, the amount of seismic data transmitted will not be great enough to justify its use and the units are not expected to work directly into the network.

5. Telemetry.

FM/FM transmission would be suitable in this application. The transmitting end of the system would consist of an audio oscillator for each information channel and an r-f transmitter, modulated by the mixed audio frequencies. Information of interest modulates the oscillator frequency. As many as 18 subcarrier channels may be attached in this manner.

For output powers of the order of 1 or 2 watts, a ground-to-air transmission range of around 100 miles may be realized when phase-lock techniques are used at the receiver. This sort of capability is obtained when standard telemetry frequencies are used (above 100 mc). A greater range would be feasible if a frequency of the order of 10 mc were used. It is felt that a transmission range of 500 miles may be achieved with one watt power at these frequencies. Admittedly the band may be very crowded, but its ability to furnish reliable long-range telemetry links should be given serious consideration especially in remote areas. The range may be increased further through the use of "constant altitude" balloons as relay stations. A total range capability of 1000 miles might be realized. Omnidirectional antennas should be used here, except at the final listening station, where it would be advantageous to use a high-gain directional antenna.

The whole unit should not require more than 5 watts. In the present state of the art, 10 lbs of batteries will operate the device for 80 hours, providing the temperature is not too low.

6. Proposed Packages.

There are a great many design possibilities associated with the problem of constructing a simple throw-away seismometer which, upon being placed, will have the greatest probability of being an effective seismic detector for all surface conditions. One approach to the problem would be to design self-orientation features into the package. This could result in a unit incorporating delay mechanisms so that, upon coming to rest, suitable leaf springs or arms would be released to right the package. A variation might be to have the seismometer suspended on gimbal rings within the package. With its center of gravity below its suspension axes, the seismometer would always be erect regardless of the orientation of the package. After motion had ceased, appropriate mechanisms could lock the seismometer in place.

Another approach would be to design the unit on the assumption that it would be physically placed in position. The design features should then be such that maximum efficiency of placement would be realized. Currently, in many velocity-type portable field geophones, seismic coupling is obtained through the use of spikes mounted on the bottom of the unit. This allows the unit to be pushed firmly into the ground with a minimum of effort, though this type of coupling is not as effective in seismic detection as anchoring to bedrock. No other single design for seismic coupling is as widely applicable as this, however, since the type of surface suitable for its use exists practically everywhere.

It is easily seen that this particular design is applicable to units dropped from the air. It is not too difficult to design an appropriate tail section for the package so that the unit falls in the manner of an arrow and upon landing, imbeds itself into the ground. The tail section can also be made to slow the descent somewhat by the use of a rotor arrangement. Electronic equipment within the unit will be transistorized and can be made to withstand very high shocks.

The merit of this scheme lies mostly in the fact that, of all the various design possibilities, the probability of achieving the intended coupling is highest.

7. Conclusions.

The design and construction of an expendable seismic unit, having the general characteristics and specifications outlined in the discussion, does not appear to present insuperable problems. The nature of the signal to be measured is such that many simple units may yield more information than fewer, more refined ones.

Aftershocks vary considerably in intensity and duration. In some cases, an individual aftershock may be as large as the original, or the activity may be negligible. The duration of activity varies from a few hours to several months or even years. It is felt, therefore, that if adequate investigation of occurrences other than those of high activity lasting for long periods of time is required, the ability to distribute seismometers over a suspicious area with maximum efficiency is essential. A coupling arrangement similar to the one discussed in Section 6 represents an approach to the problem of achieving this goal.

8. Technical Program.

Phase 1 - Preliminary experiments

Phase 2 - Development and construction of experimental model

Phase 3 - Evaluation of experimental model

Phase 4 - Construction of prototype

9. Preliminary Estimate of Cost and Personnel.

It is expected that the design and development of a prototype model can be completed two years from the date of initiation of the project.

Phase	Man-Years	Cost ($ x 1000)
First Year		
1	2	50
2	5	150
Second Year		
3	3	80
4	5	150
TOTALS	15	430

Appendix 15

USE OF MULTIPLE ARRAYS IN SEISMIC DETECTION

John Gerrard

1. Introduction

Increasing the number of detectors and the area of sampling is of great advantage in exploration seismology and it is to be expected that similar gains will be achieved by using this process in earthquake and nuclear test detection. Exploration seismologists have utilized information theory, antenna theory, and statistics to develop the criteria that have been the basis for field tests and subsequent operational procedures. Gains have been made principally in signal-to-noise improvement and in the consequent increases in reliability of interpretation.

In the nuclear detection problem, the first obvious advantage is one of better signal sampling. By sampling the ground response over an area which is small with respect to wave length, but large with respect to noise coherence, the probability of detecting any incoming coherent signal will be increased. Combining the output of the units of an array of detectors on a weighted, additive, or possibly a multiplicative basis will reduce the non-coherent noise. The increased number of detectors may also lead to a better knowledge of the directional properties of any incoming wave and permit velocity filtering to separate signal from noise.

The greatest advantage in using arrays of seismometers in the determination of first-motions will be realized through the flexibility with which this increased amount of data can be processed in the station's data processing centre for purposes of signal enhancement. The machine computations at the centre are not limited to simple fixed or shifted time combination procedures which will lead to a maximum increase in signal-to-noise amplitude ratio of $n^{\frac{1}{2}}$ (where n is the number of seismometer responses that are combined). A computer will, in fact have the capability of operating on the data iteratively by numerical processes which may produce increases in the signal-to-noise amplitude ratio by a factor greater than $n^{\frac{1}{2}}$.

The number, geometrical pattern, and areal disposition of an array in a fixed area (3 x 3 km) will be determined after consideration of several factors: the geological conditions at the station, the response characteristics of the instruments, and the apparent velocity and frequencies of the signals and noise involved.

The advantages of three-dimensional arrays with deep or shallow hole instruments must also be taken into consideration in a study of configurations.

2. Nature of the Signal

2.1. Signal and Noise Characteristics

In the series of recordable seismic vibrations arriving at a point on the surface from an earthquake or an explosion, there will be certain characteristics which will be more indicative of the nature of the source than others. Observations thus far available indicate most identification information is contained in the first-motion and the long-wave components. In working with the latter, the installation of long-period, three-component seismometers appears to be adequate.

In the case of the former, however, it is felt that much is to be gained by the use of multiple arrays. By noting properly the directional properties of the incoming energies and allowing for an instrumental and computational decrease in the noise background, the array would improve greatly the desired first-motion determination. The first-motions have a frequency content of from 1.0 to 10 cps dependent on distance, and their amplitudes, as measured in the HARDTACK experiments, fall off faster than r^{-3} at distances from the source up to about 1,100 km. They have not been recordable in the shadow zone from 1,100 km to 2,500 km, but are recordable at greater distances with increasingly smaller amplitudes. In this shadow zone, the use of arrays to study the characteristics of other phases, which thus far are not separable, should be contemplated. If in fact the arrival of these subsequent compressional wave phases, P* and Pg, is being masked by reverberation noise, then they might be found by studying the rates of travel across the array. Since P* and Pg will have apparent velocities close to 6 km/sec, and generally will cross the array in the same direction, it seems quite likely that the masking effects of the slower moving, coherent reverberation noise might be considerably reduced through computational procedures. Some of these procedures, which would constitute velocity filtering, would use time-shifted, additive and multiplicative combinations of the outputs of the various array seismometers, as noted in the paper on computers.

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The microseismic noise of greatest amplitude has about a 6-second period, and is, in general, coherent. This microseismic band would be attenuated by the properties of Benioff-type instruments which have a cutoff between 0.5 and 0.2 cps, and record the band from 0.5 to 10 cps with a maximum of fidelity. The microseismic noise in the latter band yields ground-motion amplitudes of 10 millimicrons, less than those of 6-second periods by a factor of 1,000. The coherence characteristics of this microseismic noise are thought to be quite poor, but further study is needed. If the coherence of the remaining noise is low, then simple addition of detector output at constant time will cause considerable cancellation.

The effect of near-surface reverberations which mask the arrivals of the seismic phases is important. These waves will cross a horizontal surface array with an apparent velocity of less than 3 km/sec, whereas the desired waves will arrive with apparent velocities of about 6-9 km/sec. The effect of these reverberations and microseismic activity would be decreased by the use of a vertical, down-hole array of geophones.

In a hole 15,000 feet deep, a span of 2 to 3 cycles of the first-arriving waves could be monitored by a vertical seismometer array up the hole.

The obvious portion of the vibration from an earthquake or explosion, which is considered as unneeded signal under the present criteria, is not true noise, but might become important to the problem after further study. A complete study of the ground motion from tests will be required to advance the art of detection and thus, in the experimental station, the use of the array responses will not only be of great use in determining the capabilities of existing criteria but may also lead to the development of new ones.

Any study of arrays should take this into account, and emphasis should be made on getting as complete a sample as possible, leaving time shifting, mixing, and antenna tuning to computational techniques employed on the recorded raw data.

2.2. Influence of the Environment

The geological and geographic environment of an array will influence the detectability of the seismic signals. The response from any given detector

will depend on the coupling of that detector to the earth. A good seismic contact will be required, and it would be desirable to have the seismometers on "bed rock," either near the surface or in boreholes. The units should also be placed or designed so that the effects of meteorological fluctuations will create a minimum of noise. When direct coupling to bed rock is not possible, the variations in the weathered layer should also be determined, since these parameters will affect the response in a manner which may be compensated computationally. Another parameter which must be determined is the type of microseismic activity in the area. Proximity to human activity, oceans, meteorological storms, and seismic activity will cause background noise and must be taken into account instrumentally and computationally. If the predominant microseisms are unidirectional, an array processing pattern could be prespecified and the computation set up to minimize their effect.

3. Multiple Arrays

3.1. Spacing and Geometric Configuration

In the study of the possible deployment of arrays in this detection problem, an attempt should be made to utilize information theory as applied to antennas and sampling, realizing the full capabilities of special-purpose computers. Obviously, if all the characteristics of the signal were known, including source, size and position, a stationary, optimum seismic antenna or filter could be designed. These parameters will not be specified, except for the fact that they should lie in certain ranges and they will vary over these ranges for every different signal. Since it is possible, in effect, to construct an optimum filter for various signals by computational processes on data from evenly spaced receivers, it is anticipated that only raw data need be extracted from the units of the array. These features could first be specified by the ranges of the expected signal and noise characteristics and iteratively improved by cyclic machine operations on the raw data. The optimum geometric pattern of the three-dimensional array may, therefore, quite likely be one of equal spacing on the surface and with other detectors placed at equal intervals in deep holes. This is due to the fact that any fixed pattern would, of necessity, be based solely on a

priori knowledge of the signal characteristics. Computational techniques, however, can take into account both a priori and a posteriori knowledge from the entire system output, and can, in effect, computationally tune the array output on the basis of various criteria as long as the sampling interval is sufficiently small in space and time. The uses of this generalized array pattern will also limit a violator's choice of optimum focus point.

Regardless of the array characteristics, the spacing between seismometers must be specified on the basis of other signal enhancement capabilities and completeness of coverage. The spacing should be distant enough that the noise at one site will be as incoherent as possible. By this process, the "random" portion of the noise may be decreased effectively through simple additive or multiplicative processes of mixing the detector outputs at fixed time. In exploration seismology the simple additive processes have realized an increase in the signal-to-noise ratio up to $n^{\frac{1}{2}}$, where n is the number of detectors. It is felt that with the more advanced procedures, within the scope of the computational capabilities contemplated that the signal-to-noise amplitude ratio may be increased by a factor of n or more. The deletion of the non-random noise in this detection problem will require selective filtering and more refined computational procedures such as the use of variable time-shifted cross correlations and non-linear two-dimensional operators.

There is great need for ensuring that all usable information is recorded. This requirement will best be defined by the frequencies and apparent velocities of the signals involved and the geologic environment of the array area. Care must be taken to avoid poor seismic coupling with the earth, seismic "dead spots," and back-reflection or reverberation zones.

All that has been said above on two-dimensional surface arrays may be associated equally with three-dimensional arrays. By adding vertical arrays in deep holes, the degree of coverage will be greatly increased and the signals available will, in many respects, be superior to those detected on the surface. With arrays in deep holes, there is expected to be an increase in the capability of monitoring the desired first-motion signals over several wave lengths. These data would greatly increase the knowledge of the amplitude and directional properties of the incoming vibrations. Another

sizable gain is, of course, due to the fact that the original signal-to-noise ratio is expected to be larger in this case, where surface noises and reverberations are minimized.

3.2 Signal Enhancement

Considering the most simple three-dimensional array to be one of equal horizontal spacing and another equal vertical spacing, there are definite instrumentational and computational techniques that will lead to signal enhancement.

First, the seismometers and primary recording systems would be designed to have a response similar to that of the Benioff short-period seismograph which has a natural period of 1 cps. This would reduce the predominant microseismic activity and pass the frequency band in which the first-motion information will lie. The microseismic and reverberation noise in this frequency band, which will be a component of the output of this primary system, will consist of parts of varied coherence. That part which is incoherent from one seismometer site to the next, due to its random phase characteristics, might be most effectively cancelled by simple additive mixing of the output. To decrease the effect of the more coherent noise, it will be necessary to utilize all the available information from the array. This may best be done computationally with the inclusion of all a priori and a posteriori knowledge from the seismometer sites in the immediate array and from distant arrays. Since the apparent velocity of the signal across a horizontal array will be 6-9 km/sec, and since the velocity of the coherent noise across the same array is about 3 km/sec, one of the computational techniques involved here would be that of forming a velocity filter. The data would then be combined to emphasize that portion of the incoming vibrations for which the phase velocity is higher and coherent as seen across the array. This type of noise cancellation can best be accomplished by the use of scanning techniques which incorporate iterative combinations of the various seismometer outputs with appropriate time shifting. This necessitates again the availability of the entire record of each of the seismometer responses for durations covering the signal interval. This capability can only be realized with a fairly extensive memory system.

Additional enhancement may be realized by performing a computational three-dimensional cross-correlation of the data from each of the seismometers for all possible angles of incidence and associated time delays for each point in real time. This and other computational processes are discussed at greater length in the computer paper and will probably yield increases in the signal-to-noise amplitude ratio by a factor considerably greater than $n^{\frac{1}{2}}$.

The directional properties of the incoming waves will be a by-product of all the computations, and from them, a great deal of information about azimuthal directions and the station's geologic environment may be gained. This information will be of value in determining not only the present source characteristics but will supply a continual increase in the a priori knowledge available for the interpretation of future signals. In the shadow zone it may be possible to separate the various compressional waves, such as P* and Pg, and hence some first-motion information may be gained. At a single receiver, these events are quite indefinite, but processes such as velocity filtering of the array data may show that they are separable. This possibility should be studied, and if in fact there is first-motion information to be gained, this will be another definite argument in the favor of the use of multiple arrays.

4. Conclusions

An increase in the effective signal-to-noise ratio can be realized by sampling the ground motion over a fixed area with an increased number of seismometers placed in a suitable array pattern. The signal enhancement for a given increase in the number of sampling sites for a given incoming wave will depend upon the selection of the site pattern, the manner in which the data are combined, and the numerical operations performed on the raw and combined data. These factors will vary from shock to shock and station to station. For example, if the predominant background microseismic noise is incoherent, then it will be desirable to group the seismometers at various positions in the array to combine all of the responses in a group additively at fixed time, and to operate on the group response, whereas if the noise is predominantly coherent, it would be desirable to obtain the maximum spacing between the seismometers in the array, to combine results only on a shifted-time basis, and to operate on both the individual and combined outputs.

If the signal and noise characteristics are sufficiently restricted in ranges of variation, the selection of the array pattern will be predicted by antenna theory, and will need flexibility only over the assigned ranges. These ranges may be quite large and the seismic antenna may operationally need to be quite general. This will not decrease the capability of forming a virtual seismic antenna through computational techniques operating on the responses of the individual seismometers in the original seismic antenna. The selection of array patterns will therefore be quite dependent upon the digital computer capabilities. The optimum capabilities of the array system will be realised through the computational signal enhancement made possible by the variety of iterative numerical operations which can be used on the raw or combined data in the computer.

5. Velocity Filtering

For seismic noise possessing a coherence velocity across a given array, the fact that the effective phase velocity of the noise is appreciably different than that of the signal can be exploited. Time-shifting the seismograms according to the known signal velocity, in order to obtain signal coherence, facilitates the addition or multiplication of the outputs. This process leads to enhancement of the signal and reduction of noise. The result of an example of time-shifting and addition are illustrated in Figure 1. A specific signal-wavelet was selected (as shown at the top of the figure). The same wavelet was chosen to represent the noise. The array contains five seismometers and is arranged as shown in the figure. Two noise wavelets, moving across the array in mutually perpendicular directions, combine with the signal (moving in the direction of one of the noise wavelets) and superimpose stationary random noise to make up the total output at the seismometers. The noise travels coherently across the array with a velocity of 3 km/sec. The signal and noise frequencies are in the range of 1 to 10 cps.

With an array approximately 25 km across, the approximate time-shifts are from 1 to 2 seconds. The signal, the stationary random noise, and the two coherent noise wavelets all have equal R.M.S. amplitudes. In Figure 1, traces 1 through 5 represent the seismometer outputs shifted in time so that the signals are all superimposed and appear in the approximate middle of each trace. Trace (a) is a normalized sum of the five seismometer traces and the signal is easily identified.

An alternative method is to time-shift the seismometer records according to the noise velocity to obtain coherent noise traces. Subtraction between pairs of traces substantially reduces the coherent noise. Subsequent time-shifting and adding of the resultant records to obtain signal coherence and enhancement may then be performed.

Figure 2 illustrates an array pattern and the corresponding signal traces for a particular example. In this case, the coherent noise is a random form travelling with a velocity of 3 km/sec. Superimposed on the coherent noise is a random stationary noise with an R.M.S. magnitude equal to half the R.M.S. magnitude of the coherent noise. The signal is the wavelet shown at the top of the figure. The ratio of signal to total noise is unity, and the signal velocity is 7 km/sec. Traces 1 through 8 represent the individual raw seismic records. Trace (a) is an example of the result obtained by time-shifting to superpose the coherent noise from two seismometers, and subtracting. The coherent noise is substantially reduced and an inverted, as well as erect, signal is present. When all such resultant traces are time-shifted again in order to superpose the signals of correct polarity, the inverted signals are out of phase and therefore cancel. The final result is shown in trace (b).

The signal was chosen to have signal components from $\frac{1}{2}$ to 10 cps and the noise spectrum covers a range of from $\frac{1}{2}$ to approximately 6 cps. The array constitutes a 2-km by 3-km grid and, consequently, the amount of time-shift required ranges from about 1/3 to $1\frac{1}{2}$ seconds. In order to prevent overlap between the direct and inverted signals, the subtraction pairs were chosen to be 2 and 1, 4 and 3, 6 and 5, and 8 and 7.

6. Technical Programme

6.1. Phase I — Preliminary Studies

An investigation would be made into use of information theory as it has been applied to antennas and sampling. This will require a knowledge of the signal and noise characteristics and the capabilities of the station computer. On the basis of this knowledge, a theoretical study would be made of the optimum array patterns which could be utilized under the various environmental conditions to be encountered. In this study, attention would be given to obtaining maximum flexibility. An investigation would be made into the influence of different geological, climatological, and seismological conditions on the responses of individual seismometers and of arrays of seismometers. This investigation would incorporate a study of

seismometers and installation techniques under various environmental conditions which will be encountered in the network. Criteria for the array type and site selection will be developed in connexion with this phase of investigation. On the basis of this study programme, selection would be made of the best array systems to be used under the several classes of environmental conditions.

6.2. Phase II -- Field Experiments on and Evaluation of System Decided upon in Phase I

The array systems selected in Phase I would be experimentally evaluated under the environmental conditions for which they were selected. Several mobile laboratories might be constructed to test array responses under a variety of environmental conditions. By monitoring the responses of these systems and by operating on the direct or taped outputs with a special-purpose digital computer, or a general-purpose machine, the ability of the various systems to detect and identify natural earthquakes and possible explosion tests would be evaluated. The field tests would then determine experimentally the influences of the station environment on the individual seismometer outputs and on the array capabilities. It will be desirable to test the array systems in conjunction with the system's digital computer so that the full capabilities of both of these systems can be evaluated and eventually realized.

6.3. Phase III -- Final Array Design

As a result of the field determinations, a selection of either a group of flexible systems, or one universal system controlled by a computer, would be made. Instructions concerning the field installation, maintenance, instrumental characteristics, and selection of site locations, will be presented.

6.4. Preliminary Estimate of Cost and Personnel

Phase		Man-Years	Costs($\$\times 10^5$)
1		15	4
2		15	7
3		15	3
	Total	45	14

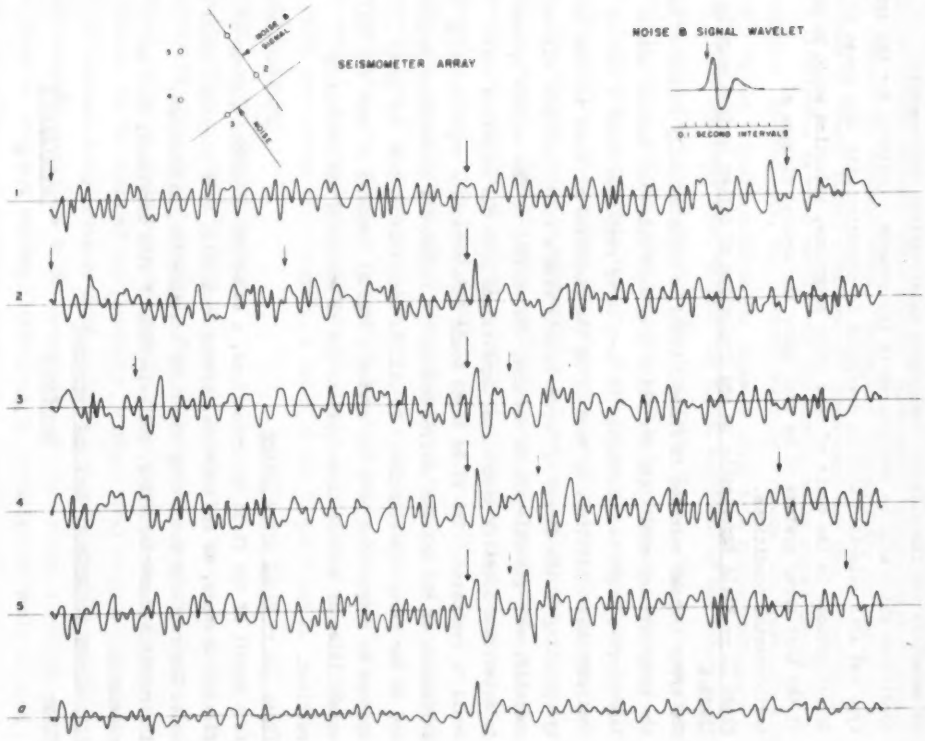

Figure 1 SCHEMATIC ARRANGEMENT AND SEISMOMETER TRACES FOR VELOCITY FILTERING

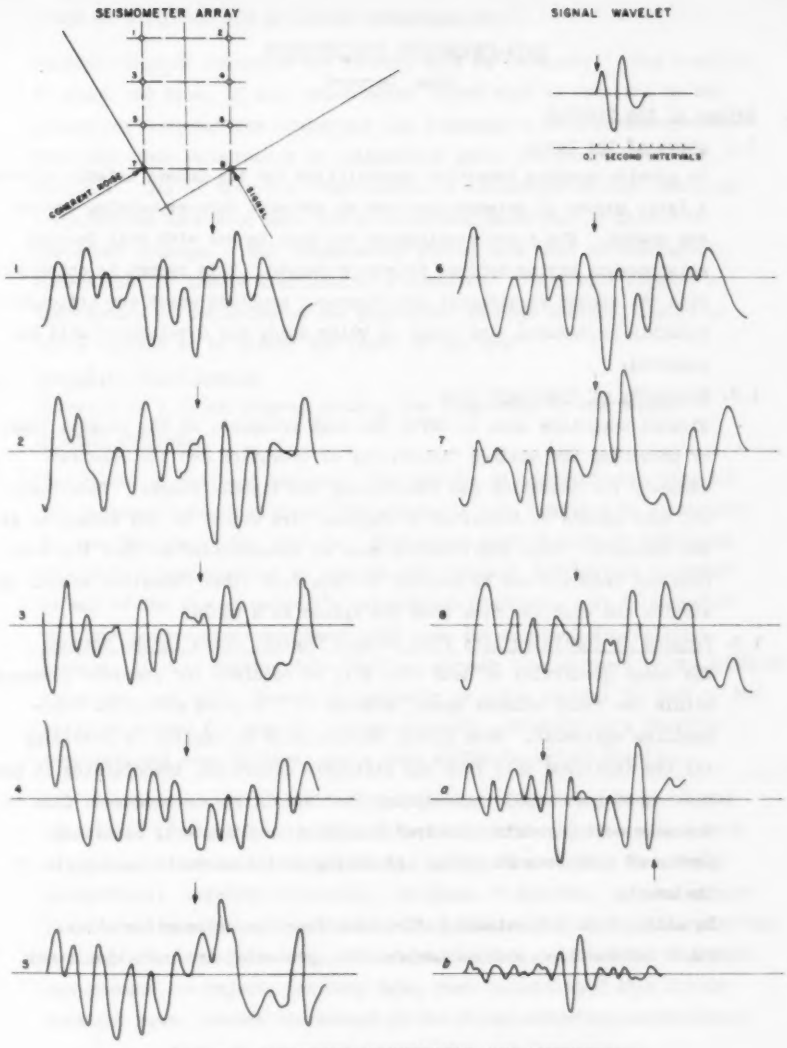

Figure 2. SCHEMATIC ARRANGEMENT AND SEISMOMETER TRACES FOR VELOCITY FILTERING

Appendix 16

DATA-PROCESSING REQUIREMENTS

John Gerrard

1. Nature of the Problem

1.1 Scope of the Paper

To provide maximum detection capabilities for the Geneva seismic network, a large number of seismometers and an advanced data-processing system are needed. The first requirement can best be met with well located seismometers having various frequency ranges. This report is concerned with the second requirement and discusses problems which are anticipated, possible procedures, and areas in which study and development will be required.

1.2. Necessity of Digitized Data

Digital computers seem to offer the best prospect, at the present time, of providing the desired flexibility of operation and the required accuracy for detecting and identifying the signals sought. Therefore, all data should be converted to digital form either at the sensor or at the computer. This digitization must be standardized so that the data from any detector can be related to data from other detectors around the station and with the data from the system as a whole.

1.3. Problem of Combining Data from Seismic Control Posts in the Network

The large quantities of data that will be required for complete coverage within the final network specifications will require extensive data-handling equipment. Each manned station must be capable of receiving all the digitized data from the station's detectors, transferring it into the computer storage, transmitting the data in raw or processed form to the main control centre (Central Headquarters Computer), receiving pertinent data from stations, and making decisions as to the origin of the event.

In addition to the seismic information from the seismometer sites, other information, such as temperature, pressure, and radiation count

could be collected and processed by the computer.

Multiple-channel reception and storage will be necessary. The position, in space and time, of each seismometer output must be retained by the processing computer for comparison and combination with pertinent data from any other seismometer or seismometer group associated with the station. All of this data must remain in accessible storage until all computations have been made and it is either destroyed or placed in permanent storage. The permanently stored data must be reasonably accessible for future examination or research. This will require a combination of transmission and high-speed storage systems, design of which appears to be within the state of the art.

1.4. Computing Requirements

Figure 1 is a block diagram showing the components of the Geneva seismic network.

The volume of data and necessary limitations on computational time for the proposed network dictate that automatic data handling be considered for use throughout the system. High-speed special-purpose computers should be interconnected to receive and transmit information recorded at any of the global network's seismograph stations. It is expected that the headquarters equipment will have the greatest flexibility. However, it will service data that has already been reduced by the station computers, and will, therefore, probably be quite similar to that of the stations except for greater storage capacity, slightly more flexible computational capabilities, and a more elaborate output display.

All the computers will need the capabilities of scanning large blocks of data in time and space; iterative time-shifting on these data such as is involved in cross-correlation; making time-varying time-scale corrections; velocity filtering; analysis of spectra; and using non-linear or time-varying operators. The process of scanning and operating on large amounts of incoming data at high speeds and deciding to retain and process, or reject, incoming data, must be performed at a fairly constant rate, whereas the extent of the signal-detection computations

will vary from time to time. This will require sufficient flexibility for reading multiple channels into the computer and also performing multiple computations simultaneously or on a time-shared basis.

These requirements will probably necessitate designing or adapting a computer especially for this problem. However, the processes themselves can be evaluated quite readily on existing general-purpose or special-purpose machines. A study of the capabilities of various numerical data-processing and signal-enhancement techniques as performed by these existing machines on data collected at the proposed experimental station and existing seismic stations will be of value in designing the final special-purpose digital computer for the stations.

It is felt that the special station computer will be a necessity in the final world-wide system. High-speed general-purpose computers are designed for a maximum of flexibility and are not optimized for handling any particular group of mathematical operations. These computers usually have only one arithmetic unit, access to only one word of information stored in the fast memory, at a time, and slow input-output speeds. The design and use of a special-purpose unit and peripheral equipment seems inevitable. Only by the optimization of such a system to meet the particular requirements does it seem possible to realize the full detection capabilities of the overall seismic network.

Figure 2 (attached) shows a typical flow diagram for the data-processing system.

2. Nature of the Seismic Information to be Analyzed

2.1. Signal and Noise Characteristics

The desired signals will be obtained from the first-motions; various forms of surface waves; and the speed, relative magnitude, direction, and time sequence of these disturbances. First-motion information will be obtained from the high-frequency vertical seismometers. Their amplitudes will be smaller than the subsequent P waves and will fall off faster than r^{-3} from the source up to a distance of about 1000 km. First-motion was unreadable past 1100 km on the HARDTACK records. The frequency of first-motion will be between 1 cps and 10 cps and will,

in general, be the highest recorded. This motion will have an apparent velocity on the ground of 6 to 9 km/sec. If the source is of the Lamb type, the motion will always be away from its origin whereas earthquake waves are generally of mixed polarity, with regions of first-motion toward and away from the source, separated by nodal lines. This pattern of first-motion directions will be an important criterion in the identification problem.

In the shadow zone there is a possibility of obtaining data from the other phases such as P* (refracted at the basaltic layer) and Pg (refracted at the granitic layer) but this must be verified by further investigation. Past this shadow zone, the amplitudes of the first-motions from explosions of less than 20 KT are so small that only through the use of signal-enhancement processes or under conditions of very low noise background could reliable first-motion data be gained.

It has been indicated that usable information may be obtained from long-period waves. This would involve comparison of the amplitudes of the longest Love and Rayleigh waves, spectral comparison of the long-period waves from earthquakes and explosions, and the epicentral distance dependence of the Love-Rayleigh wave-amplitude ratio. The raw data required would be collected from the three-component long-period seismometers.

Another promising possibility, which merits further study, is in the Lg response of the three-component seismometers for continental paths. In earthquake recordings, the vertical motion is relatively small, whereas on the available nuclear explosion records there appears to be a large vertical Lg component. These signals have periods between 1 and 4 seconds, and therefore, sensitive higher frequency three-component systems are needed to record them. Since the periods involved are close to those of maximum microseismic activity, recording of these signals will depend greatly on the level of microseismic background.

The noise in the first-motion detection problem might be classified in different groups before characteristics are defined. The outstanding group has amplitudes from 1 to 10 microns at periods of about 6 seconds.

Due to the size of this predominant and microseismic noise, great effort would be made to filter it out. Above this filtered-out band, the microseismic noise amplitudes are down around 10 milli-microns and very little is known about the characteristics. Of importance in this band is the occurrence of near-surface reverberation noise which tends to mask all but the first part of the P phase. This noise is coherent and has an apparent surface velocity of about 3 km/sec. -- considerably slower than the signal-phase velocity. Also, near areas of human activity, the computer programme must take into account the varieties of noise generated by man in this passband.

The microseismic noise levels at very low frequencies will be small, and determinations of long-wave spectral characteristics will probably not be affected by anything but barometric changes. As mentioned above, a real microseismic noise problem does exist in attempting to detect Lg. If, however, the microseismic storms are not effecting all the stations, the quiet ones may supply the needed data. Otherwise, signal enhancement techniques will be the only possible solution.

2.2. Multiplicity of Information Sources

Each of the main seismic stations on the 1000-to-1700-km grid will be the first receiving posts for relaying sizable amounts of data. According to one proposal, the stations will probably monitor the following seismic data:

10 or more samples per second from two horizontal seismometers with magnifications of 10^6, tuned to a period of 1 second

10 or less samples per second from each of the three components of the seismometers of 10^3 to 2×10^3 magnification, covering the range from 1 to 10 seconds

10 or less samples per second from each of the three components of the seismometers of 3×10^4 magnification, timed to periods between 2 and 2.5 seconds

10 or more samples per second from each of the 35 vertical unmanned seismometers in seismically active areas, recorded continuously or during interrogation periods

10 or more samples per second from each of the 100 vertical seismometers in the 3-x-3-km horizontal array surrounding the station

10 or more samples per second from each of 50 or more seismic detectors in any deep-hole vertical-array network in the 3-x-3-km area

At those stations which have long-period instruments, these responses for each component should be sampled at a rate of about 1 per second.

Overall, this amounts to a processing capability of approximately 2000 words of information per second at each station. The source and recording time of each word of information must be identifiable for computations. Also, information channels must be made available for any nonseismic information.

3. Digital Coder of Data at the Seismometer

The output of each seismometer must be digitized at some stage of its transmission to the computer. Where cable connections are possible, this digitization may be done at the computer. When telemetry is required, as in the case of the auxiliary or "throw-away" units, conversion would probably be made at the seismometer site. In practice, transmission of digital information is more reliable and offers a greater dynamic range capability than analog transmission with similar telemetry equipment. The analog-to-digital conversion and coding system required could be quite small and would require little power.

4. Digital-Computer Operations for Signal Enhancement

4.1. Preliminary Data Processing

The digitized data from the station's seismometers would be stored continuously in appropriate computer storage blocks.

One objective of reading-in all the data taken in a specific interval of time would be analysis of the surface waves detected by the long-period seismometers, since this phenomenon is expected to be recorded for even 5 KT explosions at ranges of at least 1000 km. A more restrictive criterion might be desirable, but without prior experience, this choice appears to be a safe one, since it nearly covers the required detection range. It will be advantageous continuously to process the long-period data independently.

The auxiliary seismometers would be interrogated at unequal intervals and would be read in blocks at high speed into appropriate storage locations. If there was no indication, on the basis of the available data, interrogations could be scheduled randomly to reduce the effect of intermittent jamming. The system would, however, obtain all substation data very quickly, so that it could be used in the computations to achieve reliability of interpretation.

The phase distortion of any given seismometer can be determined, and therefore, by proper filtering, can be compensated. The responses of all seismometers would be corrected to a suitable standard of response, and related to the real-time-of-arrival by phase-compensation operations in the computer. This calculation would be done automatically as the raw data is fed into the computer.

It would not be desirable to have an entire 30-day record for each seismometer in high-speed computer storage. It will, therefore, be desirable, in computer and programme design, to incorporate some means of preliminary data selection. An example of this is the following chain of computer processes which might be performed after detection of a surface wave:

a. Reverse the memory and scan the outputs of the high-frequency vertical seismometers for the amplitudes of signals.
b. Scan appropriate data from auxiliary stations.
c. Communicate with the G.H.Q. computer and adjacent stations.
d. As this data is being processed, specify iteratively the probable time range of the first-motion signal in the data blocks from each seismometer.
e. On the basis of this range information, read the appropriate data-block sections into high-speed storage for enhancement computations.
f. Make preliminary combinations of the data from appropriate array seismometers on a fixed-time and/or time-shifted basis.

This selection of the "appropriate" blocks of data is possible because the first-motion is known to have an apparent velocity of 6 to 9 km/sec. Therefore, the first-motion arrivals at two points in time and space will determine the time of arrival at other points on the surface within the limitations of the certainty of the velocity and angular determination.

Steps a, b, and c of the processes listed would be initiated simultaneously for best selection and sequence of the data to be processed. The absolute amplitude ratio of the first-motion to the subsequently recorded P waves is of the order of 1:3, and the difference will be greater when comparing the first-motion amplitudes with those of the shear and surface waves. Therefore, in looking for the first-motion, it will be advantageous to look for the anomalous amplitudes of the wave trains rather than the first-motion alone.

Existing special-purpose devices have the capability of scanning and determining the time and space location of the occurrences of amplitudes in desired ranges with a speed of about 60,000 words per second. This means that 60 seconds of data received at 100 recorders and sampled at 10 cps can be processed in 1 second. Once having defined the position of the wave train in any given response block, the possible first-motion location range will be specified. If there has been some high-frequency filtering and recording in an attempt to segregate first-motion frequencies, then this data might well be extracted at this stage. The occurrence of a large high-frequency response (4-10 cps) in the portion of the data immediately preceding the wave train mentioned will probably be indicative of the first-motion. This spectral analysis, performed by existing computers, can be accomplished at a rate of 10,000 words per second, and may be feasible if intended for only part of the data. The better the first motion's advancement in time and space can be defined, the more reliable will be the subsequent calculations. This is due to the fact that the shortness of the range of numerical data will dictate the number of calculations in real time that can be performed on the raw data. Special-purpose computers now available have the capability of handling an input-output of 200,000 words per second. This constitutes a 100:1

ratio for this application, in which the 200 available seismometers generate 10 words per second apiece. A greater problem is tape or drum memory transport speeds rather than machine access times. At this ratio it is conceivable that an indication of some signal would immediately start the transfer of data to and from low- and high-access storage. This data shuffling will require the computer to make selections of available data blocks from the various units. This decision process must be quite flexible and would require recorded data to be available in demand. Much will be learned through contact with the general headquarters computer. From it, data and interpretations received from other stations will be available, and within minutes, a station will be able to determine the approximate epicenter and size of the shock that generated the surface wave which set off the initial search at the particular station. Upon receipt of this information, application of standard earthquake travel-time curves should describe the limits of the time and space occurrence of first-motions.

It may be desirable to add the responses of groups of seismometers in the array at a fixed time as a standard preliminary operation to reduce the effects of incoherent noise and enhance the signal. It may also be advantageous to make some preliminary time shifts, either of combinations of the responses or of the individual seismometer responses. How much of this should be done will be determined by the type of array used and the data-processing procedures that evolve from research.

4.2. Combination of Data

For purposes of signal enhancement it will often be advantageous to combine the responses of several seismometers. This combination may be multiplicative and/or additive, and may be done at relative fixed or shifted times. The multiplicative, time-shifted combination of two seismometer responses is roughly equivalent to the cross-correlation techniques. It is quite possible that the cross-correlation results from several pairs, when additively combined at fixed or shifted times, will lead to a significant increase in signal-to-noise ratio. However,

in the case of first-motion studies, comparative computations will need to be done to determine the sense of the pulse from the resulting cross-correlation-type data. If the noise is incoherent and the signal is coherent over the distance between n seismometers, the addition, at fixed time, of the n seismometer outputs may increase the signal-to-noise ratio by $n^{\frac{1}{2}}$. On the other hand, if the noise is coherent but has a different apparent velocity of coherence across an array of seismometers, the time-shifted addition of responses can lead to considerable signal enhancement. Data taken at different seismometers will not be, in general, of equal worth; therefore, it may be desirable to combine the data in a weighted manner. Determination of the weighting factors will require a priori knowledge which may be externally or internally generated. The computational time requirements for the simple operations of time shifting, adding, and multiplying, are quite small. 2000 words of data can probably be selected, cross-multiplied, and added in 0.2 second. Since this is the expected per-second output of the seismometers at one station, and since these processes need not be performed continuously, the principal time limitation again appears to be the accessibility of the data which must be transmitted to the machine.

4.3. Travel-Time Calculations

Travel-time calculations will be very important in determining the distance and direction to the origin of the disturbance, and will be a prime factor in selecting the data blocks for preliminary data processing. These calculations will require the availability of standard earthquake travel-time information, the geometric position of each recording seismometer, and previous calculations of any given shock. The process will not only be one of increasing continuously the precision of locating an epicenter, but also of forming, iteratively, a more accurate determination of the position in space of the wave-fronts at any point in time. The computer programme must include retention of the final travel-time and epicenter-locating data to augment standard earthquake T-vs-Δ data for future determinations.

4.4. Correlation Techniques

4.4.1. Cross-Correlation with a Predetermined Operator

A typical process for which the special-purpose digital computer

will be optimized is the determination of cross-correlation coefficient, $\phi_{xy}(\tau)$, can be thought of as a measure of the degree of sameness, or dependence, between two information series, x(t) and y(t), when compared with a lag. The analytic formulation is given as

$$\phi_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{+T} x(t).y(t+\tau)\, dt$$

for stationary series. This form can be approximated in numerical computations by the summation

$$\phi(m,\Delta\tau) = \frac{1}{N-m+1} \sum_{n=0}^{N-m} x_n \cdot y_{n+m}$$

$\Delta\tau$ is the sampling interval and should be about 5 to 10 samples per cycle of the signals desired.

The required sample length for computing $\phi(\tau)$ depends on the use to which the result will be put, and, to a certain extent, upon the frequencies of the input function. A useful rule of thumb is that N in the equation above should be at least 10 times the maximum value of m.

Since the first-motion will, in general, represent the highest frequency in the P train, cross-correlating the individual or combined seismometer responses with the expected waveform of the first-motion will produce a maximum cross-correlation coefficient with a relative time shift τ which will indicate the position in time of the first-motion, and with a sign that will indicate the polarity of the first-motion. This operation can therefore be regarded as a first-motion enhancement filter. The first-motion wavelet will probably be well defined on a number of the 170-km-grid unattended seismometers, and may be obvious in the unmixed responses of the station high-frequency seismometers.

Determination of the waveform which could be used could be made by averaging the first-motion character from those recordings on which it is obvious and considering this form to be constant over the area in question. The mathematical operator might also be

determined from the observed changes in waveform through prediction operations on the obvious data if this time-space varying wavelet is found to be more effective, in practice, as the operator. Considerable experimentation in the location finally to be occupied would be necessary before the operator or operators were selected.

In searching, computationally, for the first-motions on discrete data, y(t) will be about 5 to 10 words in length and x(t) will be about 50 or 100 words in length. At a multiplication rate of 25μsec, each such cross-correlation will require about 10 milliseconds. If the internal data shifting takes an equal amount of time, the time required for cross-correlating one preconceived first-motion wavelet with the selected data blocks from 200 vertical seismometers would be 4 seconds. This procedure should lead to increases in the signal-to-noise amplitude ratio well in excess of the $n^{\frac{1}{2}}$ factor.

4.4.2. Cross-Correlation of Two Input Data Blocks

The mathematical procedure in this process is the same as that noted above, and differs only in the fact that x(t) and y(t) are now both considered to be individual or combined data blocks. Since the process of cross-correlation is one of determining the dependence between two sets of data, it is valuable in determining time differences between coherent data. This technique, or a similar numerical operation, will be useful as a velocity-filter process. Operating on single-and combined-array seismometer outputs, the cross-correlation computations may be utilized in an iterative process for enhancing the effects of responses related to apparent velocities of about 6 or 9 km/sec. to a greater extent than simple additive processes. This process will not yield polarity information on first breaks by itself, but by establishing the time of arrival of the desired information, it will enable further comparative calculations on a much more restricted portion of the data.

4.5. Use of Linear and Non-Linear Operators

Signal enhancement may be accomplished by operating on the data with stationary or time-space-varying functions. These operators, and the manner in which they are applied to the data, are determined by the nature of the signal and noise and the type of enhancement desired. In the application of these techniques, some of the greatest advantages of the special-purpose digital computer will be realized in that the signal-to-noise amplitude ratio increase may be by a factor in excess of $n^{\frac{1}{2}}$.

One process is the convolution of a fixed or time-space-varying function with the seismometer responses. The classical convolution $c(t_1)$ of two functions, $f(t)$ and $g(t)$, is defined through the convolution integral

$$c(t_1) = f(t) * g(t) = \int_0^t f(t - s)\ g(s)\ ds$$

which can be approximated by the summation form

$$c(t_1) = \sum_{\tau = \tau_1, \tau_2, \tau_3, \ldots t_1} f(\tau)\ g(t_1 - \tau)$$

which will require computation times similar to those of determination of the cross-correlation function. The determination of the operator $g(s)$ may be made externally or internally to the computer programme. An example of $g(s)$ might be the computed inverse form of the expected first-motion wavelet. Theoretically, this inverse operator, when multiplied with the series, and summed over an interval equal to the operator length, would yield an impulse only at the point in convolution where the signal is positioned. In practice, due to the instability of most seismic wavelets, the exact inverse is usually impossible to find. If this is found to be the case, there still appears to be the possibility of approximate inverses. An operator which has been used for the contraction and amplification of unstable seismic wavelets in the presence of background noise is the inverse of a wavelet which has an amplitude spectrum similar to the one involved, but which has minimum phase characteristics and hence is stable. A very short operator of this

nature would essentially act as a high-frequency pass filter.

Another form of filtering would be the use of certain series polynomials for various lag rates. One such operator, which has been used in exploration seismology, is represented by the time series, g(t), generated from the response f(t) at a lag rate of r with appropriate constants K

$$g(t) = f(t) + \sum_{n=1}^{N} (-1)^{n+1} K^n f(t - nr)$$

This operator acts as a band-cut filter and eliminates reverberations in shallow-water-exploration seismology. Some operator similar to this might therefore also be used to cancel reverberations in the detection problem. This is, of course, only one example of a class. Using the first three terms in the equation above, each data point of g(t) could be calculated on existing computers in less than 120 microseconds. Therefore, such a calculation on 200 seismometer responses of 40 words data length, such as proposed above, could be performed in about 1 second.

Such calculations as error operators may also be useful. These operators measure the error of prediction and hence the change in character of a record. One such statistical quantity which may be used in the running average E_i of square errors given by

$$E_i = \frac{1}{2p} \sum_{j=-p}^{+p} (x_j - \bar{x}_j)^2,$$

where 2p is the number of elements in each average, and $\bar{x}_j$ is the average of x_j over a specified range. Such an operator would indicate the change in character of the data by its change in value. As seen in more sophisticated forms, these error operators have been quite successful in determining the presence of a signal in a noise background. If 2p is equal to 20, each point E_i could be calculated on existing computers in about 1 millisecond, and the 200 responses with 40 words each could be generated in 8 seconds.

The list of operators is infinite and study would be required into the nature of the first-motion before one class could be determined to be the best. It may also be worthwhile investigating the possibilities of using

time-space-varying operators. Once these operators are specified, the calculations need not take any more time than the fixed operators. The quoted calculation times are, in fact, not lower limits, and could be reduced by proper computer design.

4.6. Spectral Analysis

These methods are applicable in determining the frequency responses of the long-period three-component instruments. As this data will be taken at only a few stations, and since the sampling interval will be about one second, the short time requirements for computations will probably permit continuous computations in the computer programme without crowding any of the higher-frequency calculations. For a data block of 100 words and 10 frequency intervals, the computations of the amplitude spectra from all of the three components will require about 1 millisecond of machine time. Calculating such factors as amplitude ratios of the longest Love and Rayleigh waves will require very little time.

5. Decision-Making Computer Operations

5.1. Detection Probabilities from Various Single Criteria

5.1.1. First-Motion Criteria

At the present time, seismic-station coverage, both in area and instrumentation, is poor. It is difficult to discuss statistics which will apply to a world-wide network without admitting a considerable margin of error. This margin will, however, be reduced when the network is in operation, since it will create the desired data.

Preliminary studies indicate that the majority of the recordable events have both compressional and dilatational first-motions. The computer may need (in its memory unit) a knowledge of the percentages of naturally occurring earthquakes in various magnitude ranges which yield only compressional motions. This data would be kept up to date.

Another requirement would be a knowledge of the reliability of the data involved and this would vary from shock to shock depending principally on the noise conditions and signal

amplitudes recorded at each of the seismometers involved. With these two pieces of information, a simple comparison technique can provide a probability of error in very little computer time.

Determining the reliabilities will not, in itself, require much computer time, but will require a great deal of a priori knowledge which will encompass all the computations that are performed on the first-motion data in the entire network. Since the data are dependent, the determination of the probability that the event is not a natural earthquake will depend on a knowledge and combination of the conditional probabilities.

5.1.2. Long Waves

Since long-wave data will, in general, be quite reliable, the probability may be based on existing knowledge. Since current estimates are based on a small number of explosions, it will in the future only be certain to the degree that the data are supplemented by other experiments. After future tests, the probability of error may prove to be negligible for the larger explosions.

5.1.3. Lg Criteria

At this time little is known about the value of this effect as a diagnostic tool.

5.1.4. Non-Seismic Criteria

The non-seismic criteria will also need to be interpreted in terms of probabilities before decisions are made.

5.2. Statistical Evaluation from a Weighted Combination of Multiple Criteria

Combining all of the separate probabilities in a weighted fashion will yield an overall probability of decision-error for each observed shock.

6. Machine Outputs

6.1. Displays

At each station computer and at the central headquarters computer, data displays will allow human monitoring. The presentation of digital probability information will require binary-decimal converters and printing mechanisms. A plotting table may be used in presenting and

mapping first-motion amplitudes and signs, epicentral locations, azimuthal directions, and non-seismic data. Another display may show the results of signal enhancement for any block of signals. This might take the form of a photographic or pen-type recorder coupled with a digital-to-analog converter operating on internally or externally stored machine data.

6.2. Permanent Storage

Data presented on the displays will only be a small fraction of the total available, and will be in all probability, only that portion of the data which is of direct consequence to the detection of nuclear explosions. It will, therefore, be advantageous to record some of the station responses and calculated data on magnetic tape for review or research purposes. Those data blocks recorded on magnetic tapes in digital form could easily be read into most of the general-purpose computers presently available, either directly or through a translator. This will allow research to be performed on any natural earthquake, or explosion, with world-wide coverage of response. When the results of this work are fed back into the station and central computers, they will enhance the reliability of the overall network.

7. Inter-Station and Intra-Station Communication

As presently conceived, the station computers would be interconnected to the headquarters computer by radio. If there are existing communication lines between distant points, these will be used. Transmission from station to station and from station to general headquarters will carry, for the most part, only filtered data or decision parameters and a minimal amount of raw data. This data transfer will, in general, be by radio, unless there are available land lines. The raw data must be transferred from the transducers to the station computer. Where feasible, this transfer will be by land line; otherwise, telemetry will be used. Telemetry will be required for the majority of the unmanned substations.

8. Conclusions

Many different criteria may be employed to detect and identify a seismic event, and the data which must be evaluated is voluminous. The number of events to be identified is also large, as some stations record about 12,000 earthquakes per year.

Speedy performance of the calculations will require automatic data-processing equipment, and it is believed necessary to design special-purpose machines optimized for this task. Since the design of such machines is a lengthy process, it is proposed that work on design considerations be started as soon as possible.

9. Technical Programme

A study programme would be undertaken in conjunction with the work on the proposed experimental station to investigate the initial processing techniques required for handling the large volumes of incoming data. Using the results from other projects in the seismic research programme, the study would determine the optimum data-collecting, transmission, transfer, and storage systems for the handling of all the relevant data expected at a single station's data-processing centre. Considerable study and development would be undertaken in order to determine the best operational techniques and equipment to evaluate all the recorded events on the basis of each of the criteria. As a result of this work, components for a model computer would be assembled and applied to the data. This model could be incorporated into the experimental station.

10. Preliminary Estimate of Cost and Personnel

	Cost ($ x 10^6)	Personnel Man-Years
1st Year	1.0	50
2nd Year	1.7	83
Total	2.7	133

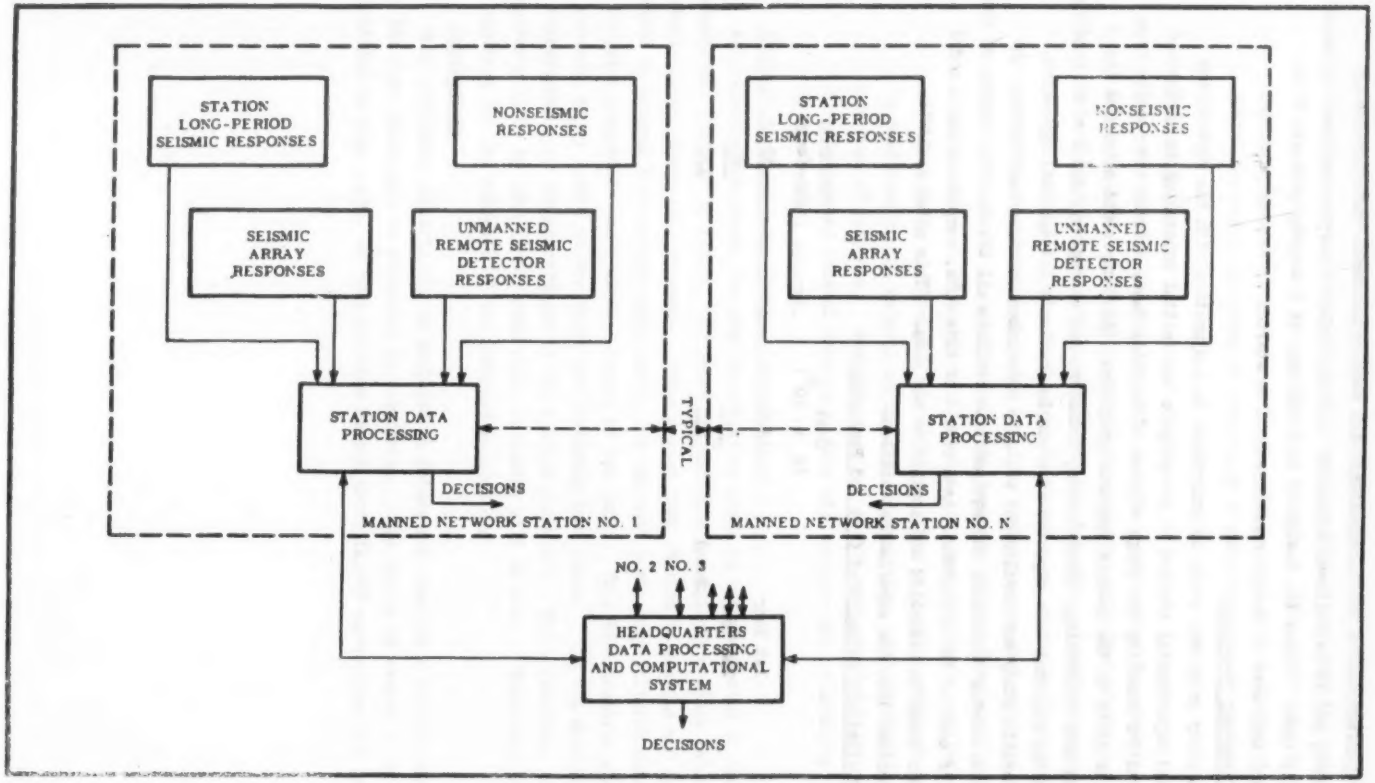

Figure 1. Schematic Diagram of Data Processing Organization in Detection System

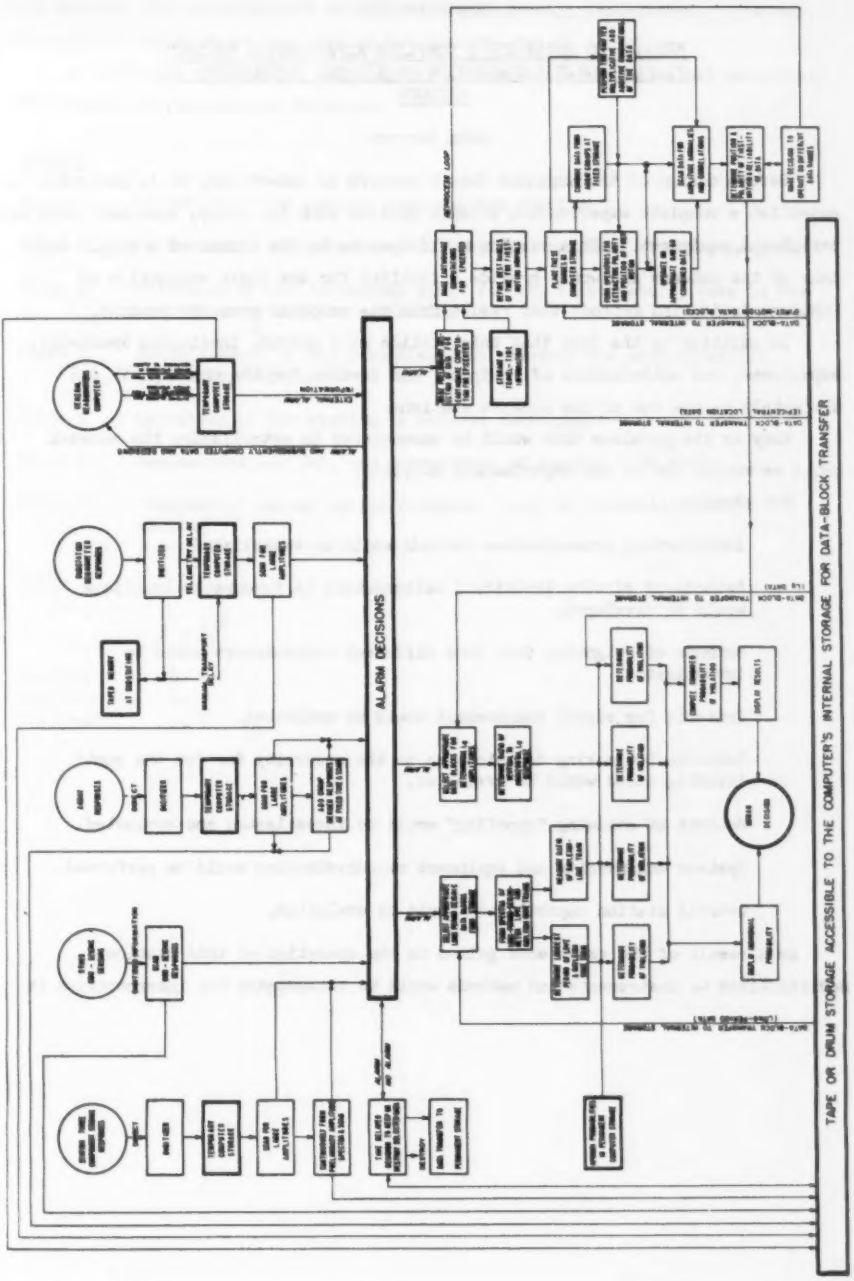

Figure 1. Schematic Diagram of Data Processing Organization in Detection System

Appendix 17

PROGRAM TO ESTABLISH A COMPLETE EXPERIMENTAL SEISMIC STATION FOR THE EVALUATION OF NETWORK INSTRUMENTS AND METHODS

John Gerrard

Before design of the expanded Geneva network is undertaken, it is desirable to establish a complete experimental seismic station with its array, unmanned units and peripheral equipment. This station would operate in the manner of a single major unit of the network and would provide a facility for the field evaluation of instrumentation and methods that result from the proposed research program.

In addition to the fact that this station will provide invaluable knowledge, experience, and optimization of equipment and devices for the network, it can ultimately become one of the network stations.

Many of the problems that would be encountered in establishing the network could be worked out at the experimental station.

For example:

Satisfactory communication methods would be established.

Methods of placing individual seismometers in favourable locations would be developed.

Methods of weighting data from different seismometers would be investigated.

Criteria for signal enhancement would be evaluated.

Criteria for making decisions as to the necessity for "on the spot" investigations would be evaluated.

Methods of avoiding "spoofing" would be investigated and evaluated.

Systems engineering and equipment standardization would be performed.

Overall station capabilities would be evaluated.

As a result of the experience gained in the operation of this station, modifications to instruments and methods would be recommended for incorporation in

the network, the establishment of which would be greatly facilitated. Further, the station could become one unit of the network when it is set up.

In addition, the station would act as a first-class seismological laboratory with excellent research capabilities.

PROGRAM

Phase 1	Selection of the general area for the station
Phase 2	Construction of equipment resulting from proposed research programs
Phase 3	Selection of the individual sites for the seismometers, both in the central array and the satellites
Phase 4	Establishment of the communications networks and central-office processing equipment
Phase 5	Operation of the station to observe earthquakes
Phase 6	Recommendations for, and measurement of special test shots
Phase 7	Fundamental seismological research using the facilities of the station

COSTS

	$ x 10^6
1st Year	6.0
2nd Year	4.0
3rd Year	3.0

Appendix 18

DEEP HOLE DETECTION TECHNIQUES

Carl Romney

1. Theoretical reasoning supported by some experimental work suggests that seismographs installed and operated at depths of several thousand feet below the earth's surface may have the capability to detect smaller P.-wave signals than those detectable at the surface. This approach is suggested by considerations which show that surface noises, which now limit detection, die off rapidly with depth; whereas the signals of interest in detecting earthquakes and explosions at great distances do not decrease with depth to the same degree. At the frequencies of interest, the experimental results to date are inconclusive. A long-term research program in being at the present time is expected to give more definitive answers by mid-1959.

2. Discussion of Theory

It is assumed that the microseismic noise recorded by short period vertical component seismographs consists of Rayleigh waves. The extent to which this assumption is true is unknown at present, although plausibility arguments exist which suggest that a high percentage of the short period noise may be Rayleigh waves. Additionally, it is known that long period microseisms (periods of 4 to 6 seconds) have large Rayleigh components. With this assumption in mind, then, it is possible to calculate the change in "noise" amplitude with depth in a uniform medium. The equation for Rayleigh waves is well known in this simple case:

$$w = fA\,(0.8475\,e^{-rz} - 1.4679\,e^{-sz})\cos(pt + fx + e)$$

where w = vertical component of motion
$f = 2\pi/L$
$P = 2\pi/T$
L = wavelength
T = period
$s = 0.3933f$ if $\lambda = \mu$
$r = 0.8475f$ if $\lambda = \mu$
λ, μ are Lamé's constants

This equation predicts that the "noise" will decrease to 20% of the surface amplitude at a depth of one wavelength and to 2% of the surface amplitude at a depth of two

wavelengths. In sandstone, * waves of about 0.8 second period will have decreased to 20% at about 1,000 meters and to 2% at about 2,000 meters. In granite, * the required depths are 2,200 meters and 4,400 meters, respectively.

The above calculations are, of course, for a medium which is grossly oversimplified in comparison with the earth. Nevertheless, it is believed that, while quantitatively inaccurate, the same qualitative features will be found in the earth. Calculations for more complex media, which should approximate the earth more accurately, are in progress at Lamont Geological Observatory at the present time.

The P-wave signals of interest also decrease in amplitude with depth. Or more exactly, the P-wave motion at the surface is twice the motion within the solid body of the earth. Thus, the very important first cycle of the P-wave decreases at a small depth to half the surface motion. For this reason, the signal-to-noise improvement expected at a given depth is equal to half the decrease in noise amplitude.

3. Experimental Program

3.1 High Frequency Work

Much work has been done by exploration geophysicists, although at higher frequencies than those of interest in earthquake or bomb detection studies. Techniques for recording high frequency seismic waves at great depth and over short intervals of time are well developed within the prospecting industry.

At somewhat lower frequencies (about 10 cps) a successful experiment was conducted by Tatel and Tuve during 1954. They observed earth motions at a depth of 3,000 feet in Pennsylvania. Results showed that the ground motions were considerably less than at the surface, indicating that the surface noise was either Rayleigh waves or upwardly refracted secondary P-waves.

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* Elastic parameters as defined by A.W. Lee, Monthly Not. Roy. Astron. Soc., Geoph. Supp., Vol. 3, pg. 83.

3.2 Low Frequency Work

3.2.1 At the frequencies of interest for earthquake and bomb detection (about 1 cps), development work has been in progress since late 1954. Technical problems are orders of magnitude greater than those associated with the high frequency work mentioned above. The reasons for the increased difficulties are associated with the following factors:

a. Since amplitudes decrease with depth in inverse proportion to the wavelength, work at 1 cps must be done ten times deeper than work at 10 cps to achieve the same change in amplitude.

b. Since the output of an electromagnetic seismometer is proportional to the frequency, electrical signals at 1 cps are only 10% of those at 10 cps.

c. Useful work in earthquake and bomb detection requires equipment which can be operated continuously.

The significance of the above factors becomes more apparent by considering that:

a. To achieve a signal-to-noise improvement of ten, the detector will probably have to be operated at depths of the order of 10,000 feet.

3.2.2 To make the measurements required to test the theory, the seismometer must be capable of measuring earth displacements of about one Angstrom unit at a frequency of one cycle per second. At this displacement, the electrical power output of a 1 kilogram seismometer would be about 10^{-17} watts. This means that any associated amplifier must have an input noise at less than this power.

3.2.3 The seismometer and associated signal cables must be capable of continuous operation in the corrosive fluids of a deep well at temperatures of 150° to 250°F and under pressures of about 10,000 pounds per square inch.

3.3 First Field Program

A preliminary field program commencing in June 1955 used a Houston Technical Laboratory's ultra low frequency seismometer. This instrument had been

designed for lowering into oil wells in connection with seismic velocity surveys. The instrument was of the "moving coil" class and had a natural period of about two cycles per second. Additional seismographs of identical characteristics were operated at the surface for control purposes. Because of time limitations, it was necessary to take the simplest possible instrumental approach which could be expected to yield valid experimental data.

The instrument was operated at depths as great as 9,730 feet. Signals from a number of earthquakes and explosions were recorded, with the general result that the signal-to-noise ratio was greater at the surface than in the hole. This unfavorable result is believed to be due in large part to the lack of tight coupling between the deep well seismometer and the earth. The difficulty in achieving a tight coupling to the earth is believed to be the most serious single problem which interfered with this initial field program.

The most encouraging results of the field program occurred at a time when the deep well seismometer was stuck at a depth of approximately 5,000 feet. This was one of the few times the instrument was known to be tightly coupled to the earth. The output of the instrument at this time was equal to its known electrical noise level, implying that microseismic noise was less than this value. It was inferred from this measurement and surface measurements that the noise had decreased by at least a factor of 6 at this depth.

Thus, while the experimental results were ambiguous, there was sufficient reason to believe that the theory might be substantiated by better experimental techniques. The advantages to be obtained if practice followed the theory were sufficient to justify a continued major development program.

3.4 Second Field Program

A new experimental program is under way at the present time. With the benefit of experience from the first program, it is expected that the equipment is improved sufficiently so that definitive data will be collected. The deep well probe will contain a velocity-type seismometer, a displacement-type seismometer and a pressure detector. The instruments are each designed to respond to earth displacements of one Angstrom at 1 cps. Considerable effort has been directed toward the design of a suitable clamping device to insure that the instrument is

tightly coupled to the earth. It is believed that the instrumentation which has been developed is as well suited to the experiment as possible, considering the present state of knowledge of the technological problems to be encountered.

A dry well drilled in granite has been selected for the experimental work. It is thought that the use of this well will eliminate many of the problems, such as bridging, cave-in, etc. which are associated with wells in sedimentary materials. The field measurement program has commenced and an analysis of the results should be available by mid-1959.

4. Future Work

4.1 System Design

Assuming that the program now under way produces data verifying the theoretical decrease in noise with depth, work will commence on the engineering design and field test of a system for continuous operational use. Following the field test, the equipment may be modified and engineered for production. Some of the chief engineering problems now expected are:

4.1.1 Considerable work may be required to develop a suitable cable. It is doubtful that any existing cable can withstand the temperature, pressure and hostile chemical environment for long periods of time at depths of the order of 10,000 feet.

4.1.2 Suitable means must be devised to prevent transmission of vibrations from the surface down the cable or along the walls of the well and into the seismometer.

4.1.3 Techniques for clamping or cementing the seismometer to the surrounding rock must be developed.

4.1.4 Mechanical and electrical components must be devised which are stable and reliable at high temperatures. It is not known whether existing techniques are suitable for the required small displacements and low power outputs.

It is estimated that work will proceed along the following lines:

		Time	Cost
Phase I	- Operational Equipment Design and Prototype Construction	1-1/2 years	$750,000
Phase II	- Operational Test	1/2 year	500,000 *
Phase III	- Production Design and Pre-production Models	1 year	500,000

4.2 Site Selection

Studies will be required to determine which geological environments are suitable for deep-hole detection stations. There are existing needs for: (1) Theoretical predictions of amplitude dependence on depth in various structures; (2) Studies of temperatures to be expected in various geographical areas; and (3) The location of areas where there are rocks in which an uncased well could be expected to remain open for a reasonable length of time. Following this, station locations could be selected and drilling could commence. It is highly unlikely that abandoned dry wells could be used for permanent stations, since most of the uncased wells cave in within a short time and many are located in proximity to active (and thus noisy) oil fields.

5. Miscellaneous

5.1 Use of Vertical Arrays

If noise amplitudes decrease with depth as expected, the noise levels will differ so much at various depths that combining the data from a shallow detector with data from a deeper detector would only degrade the data from the deeper instrument. Additionally, in view of the likelihood that the detectors will have to be cemented into the well, the operational problems associated with vertical arrays seem formidable. Vertical arrays are not recommended at this time.

5.2 Cost of Drilling

5.2.1 In sedimentary regions where detailed knowledge of the substructure is unknown, the cost of a 10,000 foot well is about $100,000 to $150,000.

5.2.2 The cost of a 10,000 foot well in granite is about $500,000 to $1,000,000.

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* Assumes an existing well can be used.

Appendix 19

RESEARCH COMPUTING FACILITIES AND A DIGITAL LIBRARY OF SEISMOGRAMS

John Gerrard

It is proposed that a computing center be established to assist in the study and analysis of seismic records. The facilities should be readily available to all those engaged in research bearing on the detection problem. This is to be interpreted in the broadest sense, for any worthwhile research into the property of seismic records and other related geophysical records must eventually enhance our capabilities in detection and identifying various sources. An example is the derivation of numerical solutions to appropriate theoretical problems.

The following facilities should be available:

1. A computer equivalent to the IBM 704 series, plus necessary peripheral equipment.

2. Facilities for converting standard seismograms into digital form.

3. A library of records of earthquakes and explosions in form suitable for machine analysis.

4. A (growing) library of basic programs which have proven useful in investigations of seismic disturbances and related phenomena. This should go on to develop into a program compiler system.

5. Personnel to assist in writing new programs and modifying existing programs.

6. Personnel for handling routine computations of checked-out programs. Presumably mail orders for computations would reach the center from various laboratories.

7. Such other facilities as will prove useful.

It is proposed that the center be organized on an "open shop" basis, so that those using the facilities assume the prime responsibility for the programs and observations. The center can only assist those making use of the available facilities. Up to a certain point the standardization of data format and programs can work to the advantage of all those concerned. The center provides a natural

way for achieving a reasonable degree of standardization.

It is essential that the work load of the center be considerably below capacity, so that new ideas and new analyses can be checked quickly. Such flexibility is essential to a research facility. Nothing can dampen enthusiasm for new ideas quite as effectively as long periods of waiting time. This requirement may make a single U.S. research center of this type inadequate after two years. To indicate the magnitude of the analysis problem it is estimated that a cross-spectral analysis of two seismograms involves something of the order of 1000 seconds of computing time on an IBM 704. The performance of 100 such analyses per day would saturate the center.

BUDGET	First Year	Second Year
Computer Rent	500,000	500,000
Upkeep	100,000	100,000
Assistance in writing programs and performing calculations	150,000	150,000
Development of digitized library	50,000	100,000
	800,000	850,000

This budget does not include funds for renting building space.

Appendix 20

CONSIDERATIONS ON THE STANDARDIZATION OF SEISMOMETERS TO BE USED IN THE GENEVA NETWORK

John Gerrard

1. Introduction

1.1. Need for Standardization

It is apparent that if the Geneva network is to be effective, measurements of seismic signals at the various control posts comprising the network must be as uniform as possible. In order to obtain any consistent evaluation of seismic records detailed knowledge of the response characteristics of the various seismic sites and their corresponding instrumentation is essential. In particular, satisfactory high speed machine analysis would be facilitated by the use of standardized seismic instruments.

1.2. Required Performance

Ideally, exact information about the spectral and time variation of the seismic signals arriving at the various receivers in the network is needed. This would include knowledge of the energy content, phase and group velocities, and particle motion. To achieve this goal, the system must measure, as accurately as possible, the ground motion in three components as a function of time. If the seismic system response can be made to follow the ground motion accurately, it remains to determine, with equal accuracy, the contributions made by earth microseismic noise and other disturbing effects. Once these conditions are satisfied, one should be able to extract the desired signals even in the presence of unwanted background.

In reality these conditions are difficult (if not impossible) to satisfy. Because of inherent instrument and seismic noise, and because of the relatively poor response of mechanical systems to arbitrary wave forms, only rather limited information about true ground motion is obtainable. In this connection, considerable effort will have to be expended in order merely to attain uniform station response, rather than realizing absolute ground motion measurements.

Some considerations in setting up a program for standardizing network stations are indicated in the remainder of this paper.

2. System Analysis

2.1. Individual Components

The manned control posts will contain individual stations and seismometers designed to receive and record particular seismic events. The various transducer units will be inertial devices covering different period ranges from a minimum period of 1/10 second to a maximum of 100 seconds. Coupled to the seismometers, there will be associated pickoff devices, galvanometers, filters, amplifiers, and possibly analog-to-digital converters. Each component of the system can be described in terms of its transfer function relating output to any arbitrary input. In this connection, ground coupling of the seismometer, and the corresponding transfer function relating ground motion to seismometer input, may be thought of as an additional system component. This function will vary appreciably from station to station and may be the most difficult "component" to standardize.

2.2. Specification of the Overall System

Each system component will contribute some noise to the system. Wind noise and general atmospherics will also contribute. The internal system noise and general atmospherics will not be coherent with the incoming seismic signal. Therefore, it can be said that, from the standpoint of nomenclature, the seismometer and all its associated equipment, plus the immediate local earth site, constitute the "receiver," and the remaining earth medium constitutes the signal "channel." Here all local microseismic noise, atmospherics, and instrument noise is random and not coherent with the seismic signal, and may be lumped together as "receiver" noise. All periodic microseisms that may or may not be related to the incoming signal, as well as reflections, refractions, and reverberations deriving from the presence of the signal, are external to the receiver and constitute "channel" noise.

3. Nature of the Data

3.1. Signal

There is insufficiency of information about the amplitude and spectral content of seismic signals in all three components for earthquakes and explosions at various epicentral distances. Therefore, it is impossible to specify optimum seismometer band widths or sensitivities. The spectral variation of seismic signals with respect to particle velocity and displacement may to some extent dictate the type of seismometers used, i.e., whether they are to be designed to respond to ground displacement, velocity, or acceleration. In making this decision, consideration will have to be given to the manner in which signal-to-noise ratios are described, as well as to the relative merits of the transfer characteristics for the three types of seismometers.

In general the principle feature of seismic signals is the nature of their transient character, and this has an important bearing on the ability of a mechanical system to respond to them adequately.

3.2. Noise

Seismic noise contains both discrete and continuous spectra. Both types vary in amplitude and frequency from place to place at a given time, and from time to time at a given place. One very strong band is located approximately in the period range of from 4 to 8 seconds. In certain areas, the variations are fairly periodic and in others, they are not. Some components of seismic noise exhibit coherence over rather large areas with a fairly well defined coherence velocity while others are strictly stationary and random. Certain noise components are generated by seismic signals and are coherent with these signals. Considerable study and measurement are necessary before adequate specifications can be made as to optimum seismometer sensitivities, bandwidths, and noise elimination processes. Whether description is in terms of R.M.S. particle velocity or displacement

will depend upon measurements of the exact dependence of the noise spectrum.

Within the "receiver", noise may originate in many places. If noise may be defined as any disturbance that masks or interferes with the wanted signal, then thermal noise, hysteresis, backlash, microphonics, and transients, as well as local random seismic and atmospheric noise, may all contribute. All of these, to some extent, lead to amplitude and phase modulation of the desired signal.

4. System Response

4.1. Seismometer and Related Equipment

Probably the most general determination that can be made about the response of a mechanical system, is that associated with input impulses of various magnitudes. The response, including steady-state response, to any transient wave form may be constructed if the impulse transfer characteristics are known.

Inertial type mechanical transducers exhibit characteristics which prevent the time history of the output response from coinciding exactly with the time history of the input excitation. The output always lags behind the input in phase by an amount dependent upon the nature of the input wave form. In addition, amplitude distortion is always present. Inertial type transducers may be divided into three classifications: response proportional to ground displacement, response proportional to velocity, response proportional to acceleration. In all three cases, maximum sensitivity is obtained when the natural period of the system corresponds to the period of the signal. This sensitivity is at the expense of response fidelity.

A re-evaluation of the system types as to their transfer characteristics for different wave forms and different system and signal periods might be justified. The evaluation might include determining what features of the various seismic signals it is more important to detect. Once this is done, a choice of a system to detect these features may be made. As an illustration, it may be decided that a highly accurate determination of the behavior of the first-break P wave front is desired. In this case, an accelerometer-type device might be used. Assuming that the initial P-break

front contains frequency components up to 10 cps, an accelerometer-type system is capable of following this motion reasonably accurately when its natural period is approximately 1/3 the period of the signal or less, and the damping is approximately half critical. In this case, a natural period of 1/30 second appears to be the maximum necessary. This fidelity is obtained at the expense of sensitivity, since the output response of the mechanical system is now only 1/10 that of the ground displacement associated with the acceleration being measured.

All filters, amplifiers, and related equipment will have individual transfer characteristics, and considerations similar to those for the seismic transducer should be given to these components.

4.2. Ground Coupling

It is difficult to predict and analyze specific problems that might be associated with ground-to-seismometer transfer characteristics. Greater difficulty may be encountered here than with any other system component. Appreciable variations in transfer behavior from station site to station site will undoubtedly occur. In addition to the general lack of knowledge as to the specification of this "component", noise will be associated with it in the form of local seismic noise immediately surrounding the site. It is quite likely that amplitude and phase distortion could both be very high. It appears that the only immediately promising approach is an experimental one, and considerable additional information must be available before adequate "plant" criteria will emerge.

4. Methods of Obtaining Transfer Functions

5.1. Transient Response

There are a number of techniques available for obtaining transfer functions once the impulse behavior of the system is obtained. Additional specific experiments may be undertaken to determine the response of a system to particular wave forms. All system components, except the ground coupling, may be calibrated in the laboratory for transient response and stability. Inter-component feedback and non-linearities may be accounted for, either through experiments on overall system behavior or through analysis of system parameters. Also, it would be easy to measure and

analyze system noise in the laboratory. The effects of ground coupling would be investigated best in the field. For transient response, the use of small scale explosives placed near the site may lead to some success. Large scale earth filled shock tube experiments using explosives may be more satisfactory since, in this case, exact knowledge of the wave form arriving at the seismometer is possible. The effectiveness of actual field tests will always be reduced through the presence of microseismic noise whereas shock tube tests may be conducted in isolated surroundings. In any event, "plant" response should be studied very extensively, possibly in greater detail than any other single calibration phase.

5.2. Steady State Response

The steady state behavior is easily derived from knowledge of transient behavior. Alternatively, it is possible to obtain, in principle, the transient response of a system once the steady state frequency response is known. Because of this and because steady state behavior is more easily obtained experimentally than transient behavior, it would be advantageous to place considerable emphasis on the study of steady state behavior of the system components, particularly the ground coupling. For the seismometer and its related instrumentation, many methods are available for measuring steady state response. Shake tables and frequency drivers of almost all descriptions are available as sources. Also, the "reciprocity" method is a simple means of obtaining seismometer calibration against a standard reversible transducer which involves no absolute measurement. The use of complex equivalent reactance, impedance graphs, and geometrical constructions, allow the extrapolation of response to frequencies somewhat beyond those actually measured. For ground coupling, the use of mechanical vibrator sources allowing adjustment of frequency and phase of the signal appears promising. In order to apply the results of steady state experiments to the construction of transient behavior, a number of conditions must be met:

The system must be linear.

The system frequency response must be bounded.

The transient response of the system begins with the system initially at rest.

The system must be stable.

In certain cases even a non-linear system may be dealt with by considering that the system is linear over a restricted operating range.

6. Error Evaluation

Close attention will have to be given to the diagnosis and methods of compensating for uncertainties due to noise, effects beyond the control of the experimenter, and adverse effects caused by necessary additions to the system. As an illustration, all forms of receiver noise, including station site atmospherics, local seismic noise, thermal noise within the seismometer and related instrumentation, microphonics and spurious transients, will have to be taken into account during the various phases of calibration.

Seismic signal reverberation due to local fault planes, the superposition of incident and reflected body waves at the free surface station site, coherent foreshock and aftershock microseisms, non-linearity, hysteresis and relaxation mechanisms within the channel or receiver, and inevitable geological variations in the local earth surrounding the site, will have to be considered in evaluating the received signal data.

The presence of narrow band stop or "notch" filters as well as particular types of electro-mechanical transducers or "pickoff" devices, plus the incorporation of certain methods of amplification, can produce undesirable phase shifts and distortions in the output response of the system. These will have to be chosen and incorporated very carefully in order to minimize undesirable effects without seriously impeding their effectiveness in performing intended functions.

7. Seismometers with Digital Outputs

There has been recent interest in simple and efficient devices capable of obtaining a direct digital representation of a mechanical signal. The advantages of such devices are that they provide a direct means of communication between mechanical systems and digital data-handling systems, and hold a great potential for increasing the accuracy and resolution of the electrical representation of mechanical motion. In the interests of standardization and uniformity among the network components, it is felt that the use of a common language with which to express the signal information is of major importance. For this reason, extensive discussion follows on digital output seismometers.

7.1 Digital Codes

There are many forms in which information can be expressed digitally. For a given application, the selection of a particular code depends on several factors. These factors include, among others, need for error prevention, requirements dictated by other equipment in the data-processing chain, and the basic nature of the conversion technique used.

In general, it is possible to express any integral number N by use of any number base which is an integer.

$$N = a_N R^N + a_{N-1} R^{N-1} + \ldots . a_1 R + a_0 R^0$$

The symbol R stands for the "radix" or base of the number system used, and is equal to the number of digits employed. Since 0 must always be one of the digit symbols used, it follows that the largest is R-1, and so the digit symbols are 0,1,2,---------R-1. Radices of practical importance are 2(binary), 8(octal), and 10(decimal). In digital notation, the presence of the appropriate power of R in each term is understood, and the various a's are one or zero, indicating presence or absence of the term.

It is relatively easy to convert between radix systems, and some are simpler than others. In particular, octal-to-binary conversion is very easy. Binary codes are particularly adapted to machine computation since the rules of arithmetic are exceedingly simple in this case. Nothing, however, prevents the use of a number base other than 2 in high-speed data-processing machines. The base 10 can be used if each decimal digit is represented by a group of four two-valued symbols. Since these can form sixteen different combinations, six of the possible combinations are not used in the representation of the ten decimal digits. Any six may be eliminated, and hence there are 16.'/6.' assignments that can be made for the ten decimal digits. These various assignments represent binary-coded decimal numbers and they may be divided into two groups. The first are fixed-weight codes, and an example would be the 8-4-2-1 code, the designation indicating the value of a one in each of the digit terms. The second are variable-weight codes and a positive fixed weight cannot be assigned to a one in each binary digit term. The number of variable-weight codes possible far exceeds the number of fixed-weight codes. It can be shown that there are only 225 fixed-weight codes possible, whereas the total number of essentially different coding schemes is 7.6×10^7. The fixed-weight codes

are usually preferred for reasons of facility of computation. But there are several of the variable-weight codes that are particularly advantageous for expressing displacement in digital form. These are called Lippel codes and they permit a substantial simplification in the construction of a reading-type coder. In this class of coder, a reading device is positioned over a code pattern in accordance with the motion to be coded. The Lippel codes allow the use of only a few separate segments in the reading device, whereas other codes require as many as there are terms in the digital representation.

While the variable-weight codes lead to simple coder construction, they will usually require a recoding operation in the equipment into which the coder is connected before the data can be processed. The conversion is not difficult, however, and in equipment of considerable computational capability, the conversion presents no undue hardship.

In a reading type coder it often happens that slight misalignment of the reading device with respect to the code pattern leads to erroneous results. An ambiguity problem exists at the transition between successive numbers in that a number not in sequence may appear during this transition. The problem is caused by the nature of the numerical representation used, which prescribes that between certain successive numbers more than one digit can change. If the numerical representation is so chosen that only one digit can change between successive numbers, then at a transition, either the old number or the next one is read, but not any other, in spite of small pattern misalignment. Codes that satisfy the requirement of a single-digit change between successive numbers are called unit-distance codes and have wide application in analog-to-digital conversion. One example of a unit-distance code is the Gray code. Other names for this code are cyclic or reflected binary.

Present digital information-processing systems are very reliable. However, operational errors are not completely eliminated. Residual errors can be reduced by self-checking or self-correcting codes. Self-checking codes permit the automatic detection of errors that may occur in transmission. Self-correcting codes permit not only the automatic detection of such errors, but also their correction. The basic principle behind both types is simple.

The number of code-symbol combinations recognized by the machine as legitimate, and therefore, accepted by it, is made smaller than the maximum possible number. This reduction is made sufficiently severe so that when a prescribed class of errors occurs in transmission, the transmitted word cannot be corrupted into another legitimate word. A simple example would be the case of a "yes - no" decision characterized by the reception of a one or zero. An error will reverse the decision. If a two-digit code is used "yes" is represented by the code 01 and "no" by 10. It follows that in this case the occurrence of a single error can never change a transmitted "yes" into a "no" or vice versa. It is only required that the receiver accept no words other than 01 or 10. Parity checking, which involves an extra digit which states whether the total number of ones in the word is even or odd, is capable of checking odd multiple errors only. It has found widespread application, because it is simple to mechanize.

To achieve self-correcting codes, the number of legitimate combinations must be reduced even further than for self-checking codes. Because of the high cost of self-correcting codes, and the good reliability now achieved in practical systems, there appears to be little application for them.

7.2. Present Coding Techniques for Electrical Signals

Coders operating on electrical signals may be divided into two groups: those in which there is an intermediate conversion to a time interval, and those in which no intermediate conversion is made. Members of the first category perform the conversion in a relatively long time (hundreds to thousands of microseconds). They result in relatively complex conversion devices, but where several information channels must be handled, some of the required components can be used by more than one channel. Members of the second category are characterized by short conversion time (of the order of a microsecond). These converters can only be shared by several channels through switching at the input or output.

Most voltage converters have essentially the same upper limit in accuracy and it is possible to achieve an accuracy of one part in from 1000 to 4000.

One example of converters using intermediate time conversion is a coder developed by the National Bureau of Standards. It is called Anodige and used the following principle of operation.

The voltage to be coded is compared with a linear, staircase voltage generated inside the converter. Each time a step is generated the contents of a counter are increased by one. When the staircase voltage agrees with the voltage to be coded, the counting action is stopped. The number of counts accumulated is then proportional to the voltage to be coded and the counter readout is the desired numerical representation. The conversion time is determined by the counting rate and the maximum number to be coded. For a counting rate of five megacycles and a ten-digit binary number, the conversion time for the largest number is approximately 200 microseconds. The accuracy is determined by the linearity of the staircase generator and the accuracy of the comparison circuit. A typical accuracy for this device is about 0.1 per cent.

Some examples of coders not using intermediate conversion to time are given below.

The operation of a common class of coders is based on comparison of the input voltage with a locally generated voltage which is altered by a control circuit until the two voltages agree. The local voltage generator is a decoder, the voltage or current sources in which are turned on or off by the control circuit. The control circuit turns on various combinations of sources until the decoder output and the voltage to be coded agree. At that time, the states of the sources indicate the desired number. A source which is turned on causes a one to be read out and a source which is turned off causes a zero to be read out. The accuracy is determined by the accuracies of the decoder and the comparison circuit. The conversion time is governed by the manner in which the control circuit develops the decoder output voltages.

Another method of coding is one in which an N-digit number is derived by the means of N single-digit coding stages in cascade. Each stage consists of a comparison circuit and a subtracter. The former compares the input voltage to a reference voltage, chosen to correspond to the value of the stage. If the comparison shows that the input is equal to, or greater than, the reference voltage, the comparison circuit reads out a one and the subtracter reduces the input voltage by the reference voltage. If not, a zero is read out and the input is passed on to the next stage unchanged. The conversion time

required by the coder with cascaded stages is determined by the operating time of the N stages in series. Typical single-stage operating times are of the order of a fraction of a microsecond, so that it appears possible that a conversion time of approximately one microsecond is fairly easily attainable where moderate accuracy (0.25 per cent) is required. This coding scheme therefore leads to faster conversion than any of the others previously described.

Various modifications have been developed on another method of coding, which departs considerably from the others in its approach. The method involves a special electron-beam deflection coding tube capable (in principle) of extremely high-speed scan (up to several million per second). The coding tube contains an electron gun and deflection plates similar to those used in conventional cathode-ray tubes. An aperture plate and an output plate are added. The openings in the aperture plate form a conventional binary code, or any other code desired. The voltage to be coded is connected to the y-deflection plates and a conventional saw-tooth voltage is connected to the x-deflection plates. The line of the code plate along which the electron beam is swept is therefore determined by the voltage to be coded, and for each line, a pulse pattern is generated at the output plate in accordance with the openings in the aperture plate. Because of the finite diameter of the electron beam, it is possible to excite two code lines at once if the input voltage deflects the beam such that the sweep lies exactly between the two code lines. This leads to a serious ambiguity problem, and for this reason, it might be desirable if the code were a unit-distance code. As previously discussed, unit-distance codes have the property that successive numbers can differ in only one digit term. This property eliminates ambiguity errors. Another method would be to increase the blocked space between the coding lines, though this would reduce the available range. Beyond the output plate, photoelectric devices convert the coded optical impulses into corresponding voltage impulses.

7.3. Present Coding Techniques for Translation and Rotational Motion

Devices for obtaining the digital representation of a linear displacement or an angular rotation are called position coders. Position coders may be divided into two broad types depending on whether a continuous or a quantized transducer is used. In the first of these, the physical motion is converted first to a proportional electrical quantity or time interval by means of an appropriate device, a potentiometer, for example, and conversion to digital form is then performed by a conventional voltage or time coder similar to those previously described. There are also new types of continuous transducers which are better suited to digital conversion. An example would be a transducer which utilizes a vibrating member, such as a string, the frequency of which can be made proportional to various quantities, such as acceleration, temperature, etc. The output of such a transducer is easily coded. In the second type of position coder, the physical motion is subdivided into incremental motions by a special quantized transducer, and conversion to digital form is accomplished by determining the number of increments contained in a particular motion. The second type can be divided further into two groups. One group is characterized by increments of position which are indistinguishable and must be counted. The other includes devices in which successive incremental positions are coded so that the number corresponding to any position can be determined directly.

Coding by an intermediate conversion to a voltage or time analog can be accomplished by a number of methods, some of which have been described previously. An additional method, which uses time as an intermediate analog signal, is a phase-shift coder. If the phase of a periodic wave form is shifted proportionally to the rotation of a shaft from a fixed reference point, the phase shift of this wave relative to a reference wave defines a time interval. This time interval is then counted by fixed-frequency clock pulses.

Frequency is also easily coded by time-increment methods. Therefore, any transducer which can convert angular or translation motion into a proportional change in frequency should be of interest for motion conversion.

Many physical principles can be used to make a pattern that can be read by automatic means. Methods currently used are electric contacts, patterns which control the transmission or reflection of optical energy, and magnetic devices. At the present state of the art, the highest accuracy is obtained through the use of optical patterns and associated reading methods. The accuracy is about 1 in 100,000, better than presently obtained in potentiometers, electrical commutators or magnetic devices. Incremental pattern devices are of two general types. In both, a signal is developed for each increment of motion. In the uncoded devices, these increment signals are indistinguishable and it is necessary to provide a means for accumulating these increments if the actual position is to be measured. It is also necessary to determine the sign of each increment signal to determine the direction of motion. To do this, at least two, and preferably more, properly phased output signals are required from the incremental transducers, and these signals must be interpreted logically to determine the direction of motion. A major disadvantage of uncoded incremental devices is that all measurement is by means of increments relative to a reference position. If one increment is somehow lost, all subsequent data will be in error by this missed increment unless a means of error-correction is provided.

The number of devices which can be constructed to provide incremental position signals or incremental motions is large. A very simple shaft-rotation coder utilizes a slotted disk. Light from two sources passes through slits to associated phototubes only when a slit is lined up with one of the many slots in the disk. Appropriate juxtapositioning of the slits with respect to each other and the disk slots permits a unique interpretation of the output of the phototubes relating to the rotation of the shaft. An electrical variation would be to use a commutator disk and brushes. Optical gratings and magnetic drums are also used in incremental devices. A number of grating coders have been built with accuracies of better than 0.0001 inch. In magnetic-drum devices, maximum counting rates of the order of 10×10^6 pulses per second are feasible.

In the incremental quantized transducers just discussed, the number representation of the physical motion is not obtained directly from the transducer but is developed in associated counting circuits. At the expense of a substantial increase in the information storage of the transducer

pattern and in the complexity of its reading system, numbers can be generated directly by the quantized transducer. These may be called coded transducers. Since an incremental pattern device already represents the least significant digit of the number, the added information consists of a separate "coarse" incremental transducer pattern for each digit of the number above the least significant. The individual pattern for each digit is usually called a code zone. Zoned pattern disks for rotational motion and corresponding patterns for translational motion are used. The two major types of coded pattern devices in present use are the commutator type, with brushes running on electrical contacts, and the optical type which has a pattern of opaque and transparent areas that can be read by placing the pattern between a light source and a photocell array. Since both brushes and light beams have finite widths, ambiguity is present and various means have been devised to overcome the problem. In the commutator type, a scheme called the V-brush method is used. One brush is used on the finest (least significant) zone, and two brushes are used on all other zones. The pairs of brushes on all but the finest zone are moved progressively further away in both directions from the reading index line as the digits become more significant. External logic circuits determine whether the lagging or leading brush in any zone is to be read at a given time, based on the reading in the next finest zone. With the addition of still more brushes, the method can be made self-switching and therefore contain its own logic. Another means, mentioned previously, of avoiding the ambiguity problem is to use unit-distance codes in which only one zone can change state between any two adjacent numbers.

7.4. New Methods and Approaches

It appears that, with certain restrictions, almost any legitimate method of coding would merit consideration for application to simple digital-output seismic transducers. In this connexion, there are a number of natural phenomena that conceivably could be exploited for their incremental or "double state" behavior. All sharp resonance phenomena exhibiting dispersion have this behavior and possibilities exist through the electromagnetic spectrum involving indices of refraction, in thermal and structural relaxation in liquids and gases involving abrupt changes in specific heat, and in mechanical and acoustical systems involving motional phase changes. Further, magneto-optical and electro-optical

phenomena, along with all wave-interference phenomena may be considered. The possibility of utilizing atomic structure as well as the optical band characteristics of metals and solids and the acoustic equivalent in multi-layered media, should not be ignored. All bounded vibrating systems capable of oscillating only in discrete modes offer further possibilities. The characteristic admittance curves of piezoelectric materials exhibit a very abrupt binary behavior with frequency and this too may be exploited.

It has already been mentioned that a useful transducer would be one in which motion, or the equivalent analog signal were converted to proportional changes in frequency. One obvious possibility for position coding is to use a variable capacitor to control the frequency of an oscillator. Also any incremental pattern device (described in the previous section) generates a pulse as it is moved. Thus, the velocity of physical devices can be coded by determining the pulse-rate frequency generated. Acceleration can also be coded in this manner. A method of achieving a variable frequency from changes in pressure may be realized through the use of a piezoelectric crystal and an oscillator. The piezoelectric crystal is driven in its fundamental compressional mode by the oscillator at a low voltage level. Upon being subjected to a change in pressure, the piezoelectric material is compressed or expanded very slightly. The oscillator and crystal constitute a so-called "Pierce circuit" where the thickness vibrations of the crystal control the frequency. Its main disadvantage is that it is very insensitive. However, with appropriate design, the method may be made acceptable.

Another coding scheme making use of piezoelectric crystals appears to present considerable promise. This method is particularly applicable to displacement-type seismometers. The whole coding device is very small, has no moving parts, and requires very little power for operation. The unit consists of a number of variable-path acoustic interferometers. The seismometer is assumed to contain a mass on a spring and a suitable damping mechanism. The purpose of the interferometers is to measure the displacement of the mass with respect to some reference point fixed to the unit's housing. For purposes of illustration, it is assumed that the mass is suspended by a spring from the top of the seismometer chamber and the bottom surface of

the mass is flat and smooth and is an efficient acoustic reflector. If one of the piezoelectric crystals is mounted on the floor of the chamber beneath the mass and connected to an oscillator so as to form a "Pierce circuit," the reflecting mass and the crystal constitute an acoustic interferometer. Changes in the mass position bring about changes in the acoustic standing-wave system between the crystal face and the reflecting bottom of the mass. These changes manifest themselves by producing conditions of resonance and anti-resonance of the acoustic system. The acoustic reaction on the crystal can be detected through changes in the plate current of the oscillator tube (this may very easily be a transistor). It is possible to mount the crystal in such a manner that the equivalent electrical quality factor of the resonant acoustic system and crystal amounts to approximately 100,000. In this case acoustic resonance brings about an extremely sharp rise in the equivalent electrical impedance of the crystal with the corresponding effect appearing in the oscillator plate current. If the acoustic medium is air, the velocity is 34×10^3 cm/sec. If a transistor is used, 500 mc is near the upper limit for operation as an oscillator. This corresponds to a wave length of 6×10^{-5} cm. Sharp maxima in the crystal impedance occur for every half wave length that the mass is moved. If the piezoelectric material is quartz or tourmaline, in the form of a thin disk, adequate operation would be achieved if the distance between reflector and crystal were 1/2 cm and the crystal diameter of the order of 1/10 cm. The power requirement for a single crystal is about 1/10 milliwatt or less. For high frequencies, the crystal may be run at one of its harmonics to eliminate the need for grinding very thin crystals. With this arrangement, it is seen that an incremental coder is obtained, and if desired, it may be used as a velocity coder by measuring the rate of generation of sharp pulses in the current through the tube (or transistor). The mounting of additional crystals, however, allows a complete binary coding of the mass displacement. If 5-binary-digit accuracy is required, 30 more crystals can be mounted near the first one. Also 30 more transistors would be required. To achieve binary coding, each new crystal is mounted at a very slightly different elevation than the others. This allows the placement of the impedance spikes at various different levels between the mass reflector and the crystals. In the final

arrangement, a number of interferometer outputs would be fed into a common channel to represent one digital zone. The 31 crystals and 31 transistors may be increased in number to gain more accuracy. Many more could be added without requiring very much space. The total area taken up by the complete coder for 5 binary digits would correspond approximately to that occupied by a pack of cigarettes. Power consumption would be about 3 milliwatts. By appropriate mounting of the crystals, the smallest increment detectable may be reduced considerably. On the other hand, much longer wave lengths can be used at lower frequencies, with the result that much grosser measurements may be taken. Further, any type of code desired may be obtained from the unit. An estimate as to the speed with which the system can adjust to rapid changes in mass displacement may be obtained by calculating the time taken for the acoustic signal to travel the distance between crystal and reflector. For a wave velocity of 34×10^3 cm/sec and a crystal-to-reflector distance of 1/2 cm, the travel time comes to approximately 10 microseconds. This is a good estimate of the conversion time for the device. One disadvantage of the system is its temperature dependence, a problem that exists in all electronic devices.

8. Conclusions

Standardization and calibration of the various seismic instruments constituting the stations of the Geneva network appears to be feasible. Calibration and limited standardization of seismometer ground "plant" on the other hand appears to require considerable experimental evaluation and study.

In the case of digital output seismometers, the use of all the available types of codes and all of the various possible approaches to the problem should ultimately yield a design of many efficient, direct digital output devices.

9. Technical Program

9.1 Phase 1 - Evaluation of Primary Detection Features of Seismic Signals and Subsequent Choice of Specific Seismometer Types

The principal signal features will dictate the most important response characteristics of the seismometers. Sensitivity and fidelity of response should constitute the major considerations.

9.2 Phase 2 - Analysis of Instrument Noise

This phase would determine thermal and internal noise present when the seismometer input is blocked.

9.3 Phase 3 - Determination of Dynamic Response

This phase would evaluate the transient and steady state response of the instrument. Additional disturbance due to hysteresis, non-linearity, microphonics, drift, parasitic transients, and so forth, would be determined as best as possible, and accounted for either as noise, or incorporated into the overall response, depending upon whether or not the processes are reversible.

9.4 Phase 4 - "Plant" Response Characteristics

This would be the most detailed investigation. Transient and steady state transfer characteristics would be determined along with the added noise due to station site environment. Isolating the true response from the noise will be difficult, and the instrumentation and development of "shock" tube or similar techniques should be considered seriously.

9.5 Phase 5 - Analysis of "Channel" Noise

Only after the complete "receiver" response has been determined will the analysis of earth microseisms and analysis of signal-related disturbances be of maximum value. It would be at this point that optimum receiver bandwidths and sensitivities, from the standpoint of their relation to the noise spectrum, may be specified.

9.6 Phase 6 - Re-Evaluation of Signal and Noise Characteristics, Spectra, and Amplitudes

At best, the calibration of the seismometers and specifications of standard acceptance levels, is an iterative process since, at every point in the program, decisions on instrumentation would have to be made based on signal and noise features that can only be measured accurately after the instrumentation is complete.

10. Preliminary Estimate of Cost and Personnel

	Cost ($ x 10^5)	Man Years
1st Year	2	8
2nd Year	2	8
Total	4	16

APPENDIX 6

SANDIA STUDY OF UNMANNED SEISMIC STATIONS IN THE U.S.S.R.

Introduction

In February 1960, the AEC[1] was requested to conduct a study of the feasibility of operating unmanned seismic stations at remote locations, taking the continental land mass and islands included in the Soviet Union as a relevant example. The Panel on Seismic Improvement, under the chairmanship of Dr. L. V. Berkner, first recommended the consideration of such stations in its report of March 1959. This Panel was formed to consider methods of improving the performance of the so-called Geneva network of 170 control posts, each equipped with specified instruments, which had been proposed by the 1958 Conference of Experts. The Berkner Panel pointed out the difficulties in obtaining adequate sensitivity for the system, even when improved instrumentation was provided at each control post, and indicated that further great difficulty existed with the use of decoupling ("muffling") techniques in connection with nuclear explosions. The Panel suggested the use of a more closely spaced network of unmanned stations as one means of improving the capability of the monitoring system. The requested study has now been completed by the Sandia Corporation in consultation with Bell Telephone Laboratories. The results, together with recommendations and costs, are included in this report.

1 See ANNEX A - Work Statement.

The main attention of the present study has been focused upon the instrumentation and communication problem of a seismic monitoring system using unmanned stations. Less attention has been given to the question of the number of stations required to attain given levels of probability of location and identification primarily because of these three reasons: (1) the instrumentation and communication problem of such a network had not previously been studied, and it was clear that if a study were made which considered a reasonable range of numbers of stations, its important results (technical feasibility and general levels of cost) could be easily transferred to other networks, (2) a major uncertainty in any attempt to assess the efficacy of any proposed network is the level of earth background noise which will be experienced, and (3) a very limited time was available for the study.

The important conclusions of the present study are that solution of the instrumentation and communication problem is technically feasible and that the cost of procuring and installing the additional equipment and communications facilities for 850 unmanned stations is of the general order of the cost of establishing two-way one-voice-band communications facilities from each control post both to international control headquarters and to each adjacent control post.

The uncertainties in earth background noise are numerous. The noise amplitude is well known to be greater in winter than in summer and to be greater near large bodies of water (oceans and large lakes).

It also varies substantially over relatively short distances even from one rock outcrop to another. Low noise levels in practice depend upon careful selection of sites and there is inadequate knowledge of how good a site one may expect to find within a given small geographical area. As a result, highly precise noise levels are at present unavailable.

Not only is the noise level clearly dependent upon geographical location but so too is the rate at which natural seismic events occur. As a result, the most effective disposition of a given number of seismic observation points will be a quite irregular one, with only enough stations in areas relatively free of seismicity to obtain an adequate probability of location. (The failure to identify rare events in such areas will be more than compensated in terms of numbers of events left unidentified by the increased probability of identification in the areas where natural events occur more frequently.)

An adequate appraisal of possibilities of such optimum desirabilities requires (1) detailed knowledge of the relative seismicity of different areas and (2) detailed knowledge of the relative noisiness of highly selected quiet sites in different areas. As a consequence, the present study makes use of nominal noise assumptions, based upon rather generalized average noise curves for quiet sites, rather arbitrarily chosen factors of worsening (to allow for the greater geographic restriction upon the search for quietness), and a simple geometric specification of

the location of the unmanned station. The levels of high noise were assumed to arise from meteorological conditions which extend over areas including many stations. Because this is the most probable time for violators to test, the station spacing was chosen to give adequate signal-to-noise ratios during these periods of storms. It was further assumed that the total land mass was seismic and that identification of the source was necessary over the entire area. The number of stations which are arrived at under these conditions can be reduced by (1) limiting the areas where identification is needed to areas of high seismicity, (2) assuming that sites can be found with lower levels of noise, (3) and reducing the number of stations which must record each event. A study which makes use of these factors and considers the advantages of optimum disposition for the manned control posts is underway elsewhere.*

The results of the present study may well be conservative as to the number of unmanned stations required for a given location for identification capability. They might also be somewhat optimistic. The present report is not intended to provide a definitive evaluation of the relation between the number of stations and the effectiveness of the system. It is intended to give as definite an evaluation as time permits of the technical aspects of the instrumentation and communication problem.

*Rand Corporation

SUMMARY

A seismic station can be installed at remote sites and left unattended for periods of 4-6 months. The operation of a network of such stations would provide invaluable information on seismic events. The design of the station, beginning with the standard 1-second Benioff vertical seismometer, is straight-forward and incorporates components which are within the state of the art. The one exception to this is the power supply which would be required at those points where radio is used as a means of communication. The communication system proposed is capable of transmitting the band of seismic frequencies from 0-5 cps and provides continuous transmission of data using either wire or one of two types of radio relay systems. The additional cost of the unmanned network required for 850 unmanned stations is comparable to the cost of establishing the communication facilities for the original Vienna network of 21 control posts.

A general summary of the estimated costs is as follows (expressed to the nearest million dollars, M standing for millions of dollars):

(1) Two-way single-voice-channel communication from each of 21 control posts to Vienna and to each neighboring control post: 170 M + 13 M/yr, if all cable; 52 M + 18 M/yr, if VHF line-of-sight radio relay. Intermediate cost for actual system.

(2) One-way 0 - 5 cps communication from each of 850 unmanned stations to nearest control post: 151 M + 18 M/yr, if wire line;

5

35 M + 11 M/yr, if VHF line-of-sight radio relay; 38 M + 11 M/yr, if tropospheric-scatter radio relay. Intermediate cost for actual system.

(3) Costs for Item (2) for different numbers of unmanned stations: Proportional to square-root of number of unmanned stations (at least over range from 200 to 2000 unmanned stations).

(4) Costs for Item (2) if 0 - 10 cps bandwidth required: One-quarter more than for 0 - 5 cps band (for any mixture of wire line and radio).

(5) Costs (engineering, procurement, and installation) for station equipment (including channel repeaters and modulators) for 850 unmanned stations: 22 M + 6 M/yr, if without security precautions; 49 M + 8 M/yr, if with security precautions.

(6) Costs of Item (5) for other numbers of stations: Approximately proportional to number of stations.

The main dangers of falsified indications from an unmanned station derive from (1) the substitution of a spurious message for the actual message by tampering with the communication channel and (2) the causing of compensating or misleading ground motions near the remote station. The first of these can be dealt with by complete encryption of the transmission from the remote station, at the price of increasing the cost and complexity

of that station and of introducing problems of maintaining the security of the key used for encryption. The installation of additional seismometers at each station seems sufficient to make tampering by artificial earth motion impractical.

The gains which are possible using a more closely spaced net of stations are qualitatively very clear. Some of the known important ones are the following:

1. Even with the assumption that the noise level is at least 10 to 50 times as small at the control post as at the unmanned station, signals which are below threshold at the control post will still be seen at the unmanned stations, provided that these stations are 2.2 to 3.7 times closer to the event than is the control post. It follows that the regions of high seismic noise, such as coastal areas, can be more effectively covered and decoupling efforts can be more successfully combated with a network of closely spaced stations.

2. Seismic events occurring near coasts or other boundaries can be viewed from many more directions, with a consequent increase in the probability of identifying earthquakes as such.

3. The availability of time of arrival from more numerous stations, some of which are much closer to the event, should substantially increase the accuracy of location of the point of the earth's surface directly above the event.

4. With unmanned stations located less than a few hundred kilometers from the seismic event, consideration can be given to the feasibility of using seismometers whose sensitivities extend upward to frequencies in the range of 10-40 cps. It is in this range of frequencies and within these distances that shots with yields of 10-100 tons, the effective yield of decoupled kiloton shots, can be detected most efficiently. Such high-frequency seismometers may prove to be useful for coverage of the regions where decoupling is possible, provided of course that the noise levels are tolerable (even less is known about noise levels in this frequency range). The price to be paid for instrumentation in this frequency range will be in a wider communication bandwidth required.

These advantages are all the more important at a time when absolute criteria for distinguishing explosions from earthquakes have not been finally demonstrated. The goal is clearly one of determining both the nature and location of the seismic impulse at the source. As the detectors are moved away from the source, the information as carried by the seismic wave is badly distorted by transmission through the complex elastic medium. After conversion to an electrical signal in digital form the signal can be transmitted to great distances without further distortion. It is clear that as a general principle the means of converting seismic waves to electrical signals should be placed as near the seismic source as possible.

The numbers of unmanned stations required to cover the Soviet Union if the nominal noise assumptions discussed in the introduction were to prove appropriate, are as follows: Under these nominal noise assumptions, a network can be designed which will provide data on an explosion of any desired size. A network of 340 stations is effective during 90 percent of the year in detecting 1.8 kt, locating 4 kt, and identifying 20 kt. Similarly, a network of 850 stations will allow the operators to detect 0.5 kt, locate 1 kt, and identify 5 kt; and with 2300 stations the operators can detect 90 tons, locate 200 tons, and identify 1 kt during 90 percent of the year.

9

ANNEX A

WORK STATEMENT

Project VT/058

1. Tasks.

a. Conduct studies of the operational feasibility of using unmanned seismograph stations, for example, spaced at about 170 kilometer intervals to supplement manned control posts spaced at 1000 and 1700 kilometer intervals in the Soviet Union. These studies should consider the following problems:

(1) Engineering aspects of the unmanned stations, to include requirements on the seismometer, transmitting equipment and power supply, tamper-proof construction, reliability, etc.

(2) Installation problems, including accessibility of sites, construction, power requirements, communications, etc.

(3) Maintenance aspects, including frequency of maintenance, degree to which host country nationals could assist, etc.

(4) Communications from unmanned posts to the manned posts, including fidelity of transmission, reliability, transmission channel space, security, etc.

(5) Recording at the manned control posts, including instrumental aids, manpower requirements, etc.

(6) Analysis at the manned control posts, including instrumental aids, manpower requirements, etc.

(7) Additional communications requirements between the control posts and a control analysis unit at Vienna, Austria.

(8) Others, as mutually agreed.

b. Conduct studies of the possible benefits of such a network of stations for the task of detecting and identifying underground nuclear explosions, considering:

(1) Noise background to be expected.

(2) Seismicity.

(3) Coastal regions.

(4) Concealment attempts.

(5) Precision of epicentral location.

(6) Others, as mutually agreed.

2. Reports. Submit a report, in 50 copies, recommending one or more specific systems of stations and including costs and manpower required for installation and operation for one year.

3. Time Schedule. It is essential that the final report be published by 15 April 1960.

2

APPENDIX 7

A METHOD OF CONCEALING UNDERGROUND NUCLEAR EXPLOSIONS

A. L. Latter
R. E. LeLevier
E. A. Martinelli
W. G. McMillan

THE RAND CORPORATION

March 30, 1959

(Declassified October 20, 1959)

R-348

SUMMARY

It is shown theoretically that nuclear explosions can be effectively hidden in large underground cavities. An estimate of the effectiveness of the method indicates that a yield of more than 300 KT could be made to look seismically like a yield of 1 KT. Experiments with both chemical and nuclear explosions are needed to test the theory.

ACKNOWLEDGMENTS

This work was undertaken at the suggestion of Dr. Edward Teller, Director, Lawrence Radiation Laboratory, Livermore, California. We are grateful to him for important technical advice. We also wish to acknowledge valuable criticism by Professor D. T. Griggs, University of California, Los Angeles.

INTRODUCTION

The possibility of concealing nuclear explosions is of vital importance in connection with the Geneva Conference on test suspension. In this report we will show theoretically that the seismic signal from an underground explosion can be greatly reduced by exploding the bomb in a large cavity.

Last summer this idea was considered, but was rejected for reasons that we now know to be fallacious. The argument went as follows. If a pressure p is suddenly applied in a cavity of radius a in an infinite elastic medium, the displacements at large distances are proportional[1] to pa^2. Because the energy W of the explosion is essentially proportional to pa^3, the displacement for a given energy is inversely proportional to a, and hence it appears that the coupling can be reduced by increasing the radius of the cavity. This reasoning, however, ignores an important physical effect. Because of preferential absorption of high frequencies in the earth, only the low-frequency components of the wave are contained in the distant seismic signal. When this effect is taken into account, the displacement at great distances turns out to be proportional, as will be shown below, not to pa^2 but rather to pa^3; therefore the distant signal is independent of the radius of the cavity. On this basis it was concluded last summer that a cavity would not be effective in decoupling the signal.

Actually the above argument is completely correct for holes that are big enough so that the pressure remains below the elastic limit of the surrounding medium. In other words, once the hole exceeds some critical size it does not pay to make it any bigger. The new discovery is that it does pay to have a hole that is big enough to eliminate any nonelastic behavior of the rock. Nonelastic behavior is bad because the medium can flow like a liquid and thus undergo large displacements.

ANALYSIS OF THE METHOD

Consider a nuclear explosion of yield W in a spherical cavity of radius a, sufficiently large that the pressure developed on the wall does not exceed the elastic limit of the medium. Assume that the energy W is suddenly distributed uniformly over the volume of the cavity and produces a step-function pressure on the wall, given by

$$p = (\gamma - 1)\frac{W}{\frac{4}{3}\pi a^3}, \tag{1}$$

where γ is a constant characteristic of the gas in the hole. It is possible to achieve such a rapid and uniform distribution of the energy by increasing the radius of the radiation phase of the fireball growth, as will be discussed below.

The Fourier tranform of the elastic displacement produced by the step-pressure p, in the wave zone at a distance r, is[2]

$$\hat{\zeta}(\omega) = \frac{pa}{8\pi\mu r}\frac{c}{\omega_0^2 + i\omega_0\omega - \dfrac{\lambda + 2\mu}{4\mu}\omega^2}, \tag{2}$$

where λ and μ are the Lame constants, c is the sound speed, and

$$\omega_0 = \frac{c}{a}. \tag{3}$$

We are interested in $\hat{\zeta}(\omega)$ for values of ω that are propagated to large distances with negligible attenuation in the earth. For the seismic network considered by the Geneva Conference, the important range in ω is from 0 to about 6 sec^{-1}, corresponding to frequencies below 1 cps. For such low frequencies the first term in the denominator of Eq. (2) dominates in the cases of interest, and Eq. (2) becomes

$$\hat{\zeta}(\omega) = \frac{pa^3}{8\pi\mu rc} = \frac{3(\gamma - 1)W}{32\pi^2\mu rc}. \tag{4}$$

Thus we find, as has been pointed out by Latter, Martinelli, and Teller,[2] that the amplitude of the distant seismic signal is proportional to pa^3, which is, in turn, proportional to W and independent of a. This is the basis of our earlier remark that the size of the hole does not affect the distant signal.

COMPARISON WITH RAINIER

It has been possible to give a simple analysis for the hole because the medium is assumed to be elastic. In the case of RAINIER, however, we must deal with a shock wave in a medium whose equation of state is not known, and with the transition of the shock wave to an elastic wave, which is not well understood. For these reasons we shall not base our comparison on any theory of RAINIER, but rather on direct experimental observations.

Measurements were made by Perret[3] of the accelerations produced by the RAINIER shot at distances of a few hundred feet from the explosion. The measurements made in the vertical direction at 371 and 451 ft are particularly useful because the medium was homogeneous and apparently elastic in this region, and the records were relatively free of extraneous reflections. The accelerometer records at these points have the form of a damped oscillatory wave, which is characteristic of an elastic medium. We now apply Eq. (4) of Ref. (2) for the Fourier transform of the displacement at a distance r:

$$\hat{\zeta}(\omega) = \frac{\hat{p}a}{8\pi\mu}\left(\frac{1}{r^2} + \frac{i\omega}{rc}\right)\frac{c^2}{\omega_0^2 + i\omega_0\omega - \dfrac{\lambda + 2\mu}{4\mu}\omega^2}, \tag{5}$$

where a is the (unknown) radius at which the medium begins to behave elastically, $\hat{p}$ is the (unknown) Fourier transform of the pressure that acts at a, and $\omega_0 = c/a$ as before.

The Fourier transform of the acceleration is, of course, $-\omega^2\hat{\zeta}(\omega)$. We have tried to fit the experimental data by choosing various values for a and different forms for $\hat{p}$. We find that the value of a is about 280 ft; therefore ω_0 is about 25 and is essentially independent of the form of $\hat{p}$. More generally, for any yield W (in kilotons) exploded in the RAINIER environment, the characteristic frequency ω_0 must scale as $W^{-1/3}$ and hence

$$\omega_0 = 25\left(\frac{1.7}{W}\right)^{1/3} \quad \text{sec}^{-1}, \tag{6}$$

since the yield of RAINIER was 1.7 KT.

From Eq. (5) and the experimental acceleration data we can now determine the Fourier transform of the displacement in the wave zone, which can then be compared directly with the same quantity for the hole given in Eq. (4). Denoting by r_0 the radius at which the accelerations were measured (371 ft and 451 ft), and by r any radius in the wave zone, we find for $r >> c/\omega >> r_0$,

$$\hat{\zeta}(\omega) = \frac{r_0^2 i\omega}{rc} \hat{\zeta}_0(\omega), \tag{7}$$

where $\hat{\zeta}_0$ is evaluated at r_0. The quantity $\hat{\zeta}_0$ is easily evaluated from the following expression:

$$\hat{\zeta}_0(\omega) = \frac{1}{2\pi i\omega} \int_0^\infty \dot{\zeta}_0(\tau) e^{-i\omega\tau}\, d\tau, \tag{8}$$

where $\dot{\zeta}_0(\tau)$ is the velocity at r_0 as a function of time. For the values of ω of interest, namely below about 6 sec^{-1}, we see from Eq. (6) that ω is less than ω_0 provided $W < 100$ KT. In this case the exponential in Eq. (8) is approximately unity for the important part of the integration ($0 < \tau < 1/\omega_0$), and Eq. (8) reduces to

$$\hat{\zeta}_0(\omega) = \frac{d_0}{2\pi i\omega}, \tag{9}$$

where d_0 is the displacement at r_0.

From Eqs. (7) and (9),

$$\hat{\zeta}(\omega) = \frac{r_0^2 d_0}{2\pi rc}. \tag{10}$$

This quantity is to be compared with the corresponding quantity for the hole given in Eq. (4). In what follows we affix the subscript h to all quantities referring to the hole. Taking the ratio of Eq. (10) to Eq. (4), we obtain

$$\frac{\hat{\zeta}(\omega)}{\hat{\zeta}_h(\omega)} = \frac{16\pi}{3(\gamma - 1)} \frac{c_h}{c} \frac{\mu_h r_0^2 d_0}{W}. \tag{11}$$

For RAINIER the quantity $r_0^2 d_0 = 2 \times 10^9$ cm^3 or 2.4×10^9 cm^3, depending on the measurement station. Choosing the smaller value, setting $W = 1.7$ KT $= 7 \times 10^{19}$ ergs, and letting $\gamma = 1.2$, which is appropriate for air under the conditions of interest, we find for the decoupling factor

$$\frac{\hat{\zeta}(\omega)}{\hat{\zeta}_h(\omega)} = 2.4\,\frac{c_h}{c}\,\mu_h\,, \tag{12}$$

where μ_h is in kilobars (kb). If the hole were in the RAINIER medium, $c_h = c$ and $\mu_h \sim 20$ kb, and the decoupling factor would be ~ 50. Obviously it is desirable to make the hole in a stronger medium, e.g., salt, for which $c_h \sim 2.5c$ and $\mu_h \sim 100$ kb. The decoupling factor in this case is ~ 600. This number should be reduced somewhat because the strong medium will couple eventually to softer surroundings, and an overshoot will occur. This overshoot can be at most a factor of 2, and therefore we have a decoupling factor of at least 300.

Another comparison with RAINIER can be made on the basis of the U.S. Coast and Geodetic Survey seismic measurements at a distance of about a kilometer. These measurements showed that the energy in the near seismic field, outside a radius of a few hundred feet, was approximately 5 per cent of the total yield.[4]

The total seismic energy radiated by the hole is

$$E_h = \frac{\pi}{2}\frac{p^2a^3}{\mu}, \tag{13}$$

where, as before, p is the step-pressure in the hole of radius a, and is related to the total yield W through Eq. (1). To ensure that the frequency analysis of the seismic wave produced by the hole is comparable to that of the RAINIER shot, we must choose $a \simeq 280$ ft. Again setting $\mu = 20$ kb, we find that $E_h = 2 \times 10^{-5}W$. Hence the seismic energy from RAINIER was about $5 \times 10^{-2}/2 \times 10^{-5} = 2500$ times as great as that expected from the hole. Because the displacement is proportional to the square root of the energy E_h, it follows that the decoupling factor is $(2500)^{1/2} = 50$. This figure is in excellent agreement with our previous estimate for a hole in the RAINIER medium.

SIZE AND SHAPE OF THE HOLE

We have seen theoretically that the seismic signal produced by an explosion in a hole in a strong medium will be hundreds of times smaller than that from the same yield under RAINIER conditions (in Nevada tuff without a hole). To what extent such a large decoupling factor can be realized in practice depends mainly on our being able to obtain a big hole in the right kind of medium.

The size of the hole required is proportional to the yield of the explosion and is inversely proportional to the pressure to which the surrounding medium can be subjected without behaving nonelastically. Both plasticity and cracking must be avoided. The latter may impose a severe limit because most rocks possess little strength in tension. Precisely what the limiting pressure is must be determined from experiment, but in the meantime it seems safe to say that the elastic requirement will be fulfilled if the explosion pressure does not greatly exceed the overburden pressure. The reason for this is that the overburden produces a compressive stress that can be relieved by the explosion without putting the medium into tension.

Considering the depth at which cavities can be easily "washed out" in salt domes (which seem to be a particularly suitable medium), an explosion pressure of about 150 atm seems feasible. Using 150 atm, it is easily calculated from Eq. (1) that the volume of the hole must be 3×10^6 ft^3 (a radius of 90 ft) for a yield of 1.7 KT, where we have set $\gamma = 1.2$, appropriate to air under the assumed conditions. In general the volume of the hole must be approximately

$$V = 3 \times 10^5 \frac{W_{\text{KT}}}{p_{\text{kb}}} \text{ ft}^3, \tag{14}$$

where W_{KT} is the yield in kilotons, and p_{kb} is the maximum permissible pressure in kilobars.

It may be necessary for practical reasons to use a nonspherical hole. If so, the ratio of the major to the minor radius must not be so large that the explosion energy is effectively trapped in less than the total volume of the cavity. This problem has not been studied in detail, but it seems clear that a ratio of three or four is quite safe.

Assuming that pressure spikes on the wall of a nonspherical cavity can be avoided, there is still the question of the nature of the seismic radiation produced, how much, and at what frequencies. This question, too, remains to be studied. A crude analysis suggests that for a class of prolate spheroids of fixed volume, the total seismic energy will not vary significantly. Furthermore, the frequency spectrum may be shifted somewhat toward higher values corresponding to the minor dimension of the spheroid. If the spectrum is shifted upward, and if the total seismic energy is the same, then making the hole nonspherical will further reduce the distant seismic signal.

NATURE OF THE PRESSURE PULSE

In air at density ρ, the shock wave from an explosion of W kilotons forms at a radius given by

$$R = 11.5 W^{0.3} \left(\frac{\rho_0}{\rho}\right)^{0.5} \text{ ft}, \tag{15}$$

where ρ_0 is the density of normal sea-level air. If the radius of the hole is larger than R, the air will shock up and the pressure experienced by the wall will rise for a short time considerably above the average pressure in the hole. Provided such a pressure spike does not cause the surrounding medium to behave nonelastically, it will not increase the distant seismic signal, because the spike lasts for a time that is very short compared with the periods of the waves that can propagate to large distances. As an example, consider an explosion of 1.7 KT in a spherical hole of radius 130 ft. If the hole contains air at normal density, the wall will experience a pressure spike of about a kilobar acting for a few milliseconds. Thereafter the pressure on the wall will be sensibly the same as the average pressure in the hole, namely about 50 atm.

We do not know whether a kilobar acting for a few milliseconds will cause any important nonelasticity. Such a pressure may well be below the plastic limit and of too short duration to produce large tensile hoop stresses. However, if it should be necessary to reduce the pressure spike or to eliminate it entirely, this appears to be easy to do by partially evacuating the cavity or by partially replacing the air with hydrogen gas. Either of these measures will increase the radiation phase of the fireball growth, allowing less energy to go into shock motion. For example, if in the case we have just considered the air density in the cavity is reduced to 0.01 normal, the radiation phase will extend to the full 130-ft radius. In this way the pressure on the wall can be made approximately a step-pressure of 50 atm, with no spikes.

In addition to the possible pressure spike from the shock wave, the hot gas in the cavity will interact with the wall and cause some vaporization of the surface. This effect will produce a recoil shock pressure that must be added to the static pressure of the gas. The magnitude of the shock depends on the rate of vaporization and hence sensitively on the temperature of the hot gas. For the case of 1.7 KT in a 130-ft hole containing normal-density air, the average temperature is only

~1 ev, and the pressure due to vaporization is utterly negligible. If, however, the hole is evacuated to 0.01 normal density to eliminate the shock, the temperature will be ~12 ev, and it is not quite certain that the vaporization pressure will still be negligible, but rough calculations suggest that this is likely. If the vaporization pressure should prove to be appreciable, it can be eliminated simply by introducing additional material into the hole to soak up energy and to lower the temperature. This additional material should be in the form of foils that are thin, to absorb energy rapidly, and that are oriented along radial lines so as not to impede the growth of the isothermal sphere.

A possible further advantage of the use of foils is that some of the energy they absorb goes into nonpressure forms such as latent heats of melting and vaporization. While it does not seem likely that the pressure could be greatly reduced in this way ih a time that is short compared with the period of the important seismic waves, it might be reduced by as much as one-half to two-thirds. This point needs further investigation.

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APPENDIX 8

CONGRESS OF THE UNITED STATES

JOINT COMMITTEE ON ATOMIC ENERGY

May 14, 1960

General A. R. Luedecke
General Manager
U. S. Atomic Energy Commission
Washington 25, D. C.

Dear General Luedecke:

The Joint Committee staff is presently preparing the April 19-22 public hearings on Technical Aspects of Detection and Inspection Controls of a Nuclear Weapons Test Ban for printing. As you know, the Summary-Analysis of the hearings has been printed and distributed. We hope to have the hearings printed within the next several weeks.

The Commission, in co-operation with the Department of Defense and the State Department, is preparing a bibliography which will be included in the hearings' print. Dr. Spofford G. English in your office is co-ordinating this project.

In addition to the bibliography and other technical papers, which will be included in the appendices to the Committee print, it is believed that the following data would also be desirable:

(1) A resume of the number of people, materials, and overall cost involved in the conduct of

a) a single underground test

b) a single high altitude test, and

c) a series of underground and high altitude tests.

It will be expected that this information would be readily available in an unclassified form from previous tests conducted by the United States.

(2) A report or summary of the results from the underground tests in Hardtack II, similar in form and content to the Livermore Laboratory report made public on the Rainier September 1957 test. A similar summary of results of high altitude tests would also be helpful.

The above has been discussed informally by the Joint Committee staff with the Division of Military Application and it is understood that the material can be prepared without too much difficulty and made available for the hearing print. For your information, the Defense Department has been requested to furnish an unclassified description of pertinent AFOAT and AFTAC programs, including a summary of research and development work to date in the test detection field.

Thank you for your assistance in this matter.

Sincerely yours,

James T. Ramey
Executive Director

JTC:me

U.S. Atomic Energy Commission
Washington 25, D.C.
June 8, 1960

Mr. James T. Ramey
Executive Director
Joint Committee on Atomic Energy
Congress of the United States

Dear Mr. Ramey:

Your letter of May 14, 1960, requested unclassified information on the effort involved in the conduct of underground and high altitude tests and a summary of their results. As might be expected the effort involved could vary several fold depending upon the complexity of the test, the extent of information to be derived and the urgency of the test.

HARDTACK Phase I consisting of 16 announced detonations (3 of these were high altitude) held in the spring and summer of 1958 at the Eniwetok Proving Ground, incurred AEC costs of $68,000,000. With DoD costs of $114,000,000 the total costs were $182,000,000 for this operation; missile costs for the high altitude events were borne by the DoD.

HARDTACK Phase II consisting of 19 detonations (4 of these were underground) held in the fall of 1958 at the Nevada Test Site, incurred AEC costs of $16,000,000. By using our previous tests as a guide, the following estimates of AEC costs have been prepared:

1. A single underground test at the Nevada Test Site, assuming the use of existing physical capabilities and staffing at that site, is estimated to cost $2,000,000 to $3,000,000 depending upon the depth and complexity of the detonation. This estimate includes materials for the construction of the underground tunnel drift or hole and instrumentation of the shot. It would involve approximately 250 construction and support personnel presently on hand and about 50 scientific and technical people. Existing facilities at NTS which would be utilized in the support of such a single detonation represent an investment of several million dollars.

Mr. James T. Ramey

2. A single high altitude test, assuming an existing launch facility could be used, is estimated to cost $12,000,000 to $20,000,000 depending upon the type of carrier missile required. Missile cost and the cost of instrumentation and other hardware are included in this estimate as well as the support of the 300 to 400 personnel who would be required.

3. A series of 20 underground and high altitude detonations -- 8 high altitude and 12 underground -- is estimated to cost $100,000,000 to $150,000,000 and would involve about 1500 personnel. The underground shots could be conducted at the Nevada Test Site using existing capabilities, including, in part, existing tunnels and holes. The high altitude detonations would require a new missile launching site. For the high altitude shots, which would probably be conducted at a remote site, considerable DoD support would be required, probably in the range of $50,000,000 to $100,000,000.

Cost of devices for these detonations has been excluded from the above cost estimates. Also, due to the inability to identify specific materials involved without knowing the exact tests to be conducted and the devices or missiles to be used, listing of materials has not been included. However, some of the types of materials required include tunnel timbering and supports, signal and power cables, diagnostic instrumentation, missiles, rockets, miscellaneous construction equipment, and other supplies incident to camp establishment.

In order to bring to your attention as early as possible the requested test results mentioned in paragraph (2) of your letter, Col. Lunger of your staff was contacted by telephone on May 20. He was advised that the unclassified report of the results of HARDTACK II is given in UCRL report No. 5626. A copy was sent to Col. Lunger on May 20. He was also advised that no similar unclassified official summary of high altitude tests has been prepared so far as could be determined. However, two existing unclassified articles on the high altitude tests were cited. These appeared in the August, 1959, Journal of Geophysical Research, and the May, 1959, issue of Nature Magazine, Vol. 23. Not mentioned was an AEC/DOD press release dated June 15, 1959, and furnished to the JCAE in advance which described the results of high altitude detonations over Johnston Island during HARDTACK. A copy is enclosed.

The Lawrence Radiation Laboratory has also prepared a report on rock changes and displacements resulting from two underground detonations, Rainier and Neptune, UCRL 5757, which might be helpful. A copy is enclosed for your possible use.

I hope that the above information will meet your requirements. Please advise me if any other information is desired.

Sincerely yours,

/s/ A. R. Luedecke

General Manager

Enclosures:
1. Press Release dtd 6/15/59
2. UCRL Report No. 5757

UNITED STATES
ATOMIC ENERGY COMMISSION

UNITED STATES
DEPARTMENT OF DEFENSE

Washington 25, D. C.

No. B-94
Tel. HAzelwood 7-7831
Ext. 3446

FOR IMMEDIATE RELEASE
(Monday, June 15, 1959)

NOTE TO EDITORS AND CORRESPONDENTS:

Attached for your information is a report on results of high altitude nuclear detonations over Johnston Island during the HARDTACK series in the Pacific in 1958. This information has been supplied to the Joint Committee on Atomic Energy and the Office of Civil and Defense Mobilization.

ATTACHMENT

RESULTS OF THE TEAK AND ORANGE SHOTS
IN THE 1958 HARDTACK SERIES

During the HARDTACK nuclear weapons test series in 1958, JTF 7 composed of personnel from the Department of Defense, Atomic Energy Commission and their contractors, conducted a high altitude weapons effects program to obtain information on the effects of nuclear detonations at high altitudes. The program was carried out in coordination with the Atomic Energy Commission.

To achieve the objectives of the program, two high altitude shots were fired in the vicinity of Johnston Island, approximately 700 miles Southwest of Honolulu, Hawaii. The first shot named TEAK was detonated on July 31, 1958, at 11:50 p.m., Johnston Island time, at an altitude in excess of 200,000 feet; the second shot named ORANGE was detonated at an altitude of about 100,000 feet on August 11, 1958, at 11:30 p.m. The nuclear devices were carried aloft by missiles and were the first megaton devices ever detonated in the stratosphere by the United States.

As on all Department of Defense weapons effects shots, a number of measurements were made including those of blast, thermal radiation, and electro-magnetic effects. Some of the results obtained from the TEAK and ORANGE shots are discussed in the following paragraphs.

AURORA AND VISIBLE EFFECTS

With respect to visible effects, TEAK and ORANGE were by far the most spectacular shots ever fired by the United States. TEAK produced a bright fireball which grew rapidly and immediately started to rise at a rate of approximately 1/2 to 1 mile per second. An aurora developed from the bottom of the fireball and spread rapidly to the north. The fireball reached a diameter of approximately 11 miles in 0.3 second and a diameter of better than 18 miles in 3.5 seconds. The fireball glowed brightly for about 5 minutes. The fireball of the ORANGE shot developed much more slowly, and the aurora, which was somewhat less pronounced than TEAK, did not appear until the fireball had risen.

These visible auroral displays were caused by electrons produced by or arising from the explosions. The particles were trapped along the magnetic field lines of the earth to produce the effects described. Gas molecules in the earth's upper atmosphere were brought to luminosity by the electrons to produce the various colors observed.

THERMAL RADIATION EFFECTS

The intensity of thermal radiation (heat) from the TEAK explosion, measured on the earth's surface at Johnston Island, was insufficient to produce first degree (least serious) burns in human beings.

For the ORANGE shot, no thermal radiation measurements were obtained due to cloud cover that existed at detonation time.

The program to measure thermal radiation from the TEAK and ORANGE shots included a biomedical project using rabbits to investigate the hazard of burns to the retinal tissues of the eye.

For many years the clinical phenomenon of retinal damage caused by the radiant energy of the sun has been known and numerous cases have been documented. Most of these cases have occurred while watching solar eclipses without eye protection; thus, this type of retinal lesion has become known as "eclipse blindness." Since the fireball of a nuclear detonation attains internal temperatures comparable to that of the sun, the predicted thermal energy release is of sufficient magnitude to cause concern about retinal damage in human beings who view nuclear detonations without proper protection. In order to receive permanent serious impairment of vision from a high-altitude burst, an individual would have to be looking directly at the nuclear detonation at the time of burst.

From previous tests at the Nevada Test Site and the Eniwetok Proving Ground, the thresholds for retinal damage had been generally established for detonations at or near the earth's surface.

The primary objective of the TEAK and ORANGE biomedical project was to determine the extent of retinal damage

caused by exposure to a high-altitude, high-yield nuclear detonation. Rabbits were placed at distances up to 300 nautical miles from the point of detonation in order to obtain the necessary data.

The biomedical project showed that a very high altitude nuclear explosion can be particularly damaging to the eye because of the rapid rate at which the power pulse delivers thermal energy and the relatively low atmospheric attenuation encountered. A high-altitude detonation in the megaton yield range, such as TEAK, delivers a great percentage of its thermal energy during a small fraction of a second after the detonation. Consequently, with a blink-reflex time of just over a quarter of a second for the rabbit and less than a quarter of a second for man, nearly all of the radiant exposure from a very high-altitude burst is received by the retina before the eye can be protected by blinking if the person is looking directly at the burst at the time of detonation. This is in contrast to low altitude detonations of the same size, where the power pulse is much slower in overall delivery of its thermal component and where the blink reflex can provide a measure of protection.

Small retinal burns were produced in the rabbits at distances up to three hundred nautical miles. Burn diameters consistently correlated with distance from the burst, with progressively smaller lesions being encountered at increased distances. For example, the burn lesions were approximately 2mm in diameter at about 40 miles distance, decreasing to 0.5mm at 300 miles. Corresponding lesions of smaller diameter might be expected at larger distances provided the burst height were great enough to allow a direct view of the fireball over the edge of the horizon. Curvature of the earth will cause the position of the fireball to be below the horizon, and therefore incapable of inflicting retinal damage.

In order to preclude damage to the Sooty Tern, a large bird indigenous to the Johnston Islands, special precautions were taken during the ORANGE shot. A water spray simulated rain and kept the birds grounded.

Smoke together with local clouds further attenuated thermal effects.

No precautions were necessary for the TEAK shot due to its higher altitude. The protective measures for the ORANGE shot were successful.

EFFECTS ON RADIO COMMUNICATIONS AND RADAR

Another objective of the Johnston Island tests was to determine the effect of high altitude nuclear detonations on radio and radar transmissions caused by reflection and absorption of the electromagnetic waves and disturbance of the ionosphere.

In general, the electronic interference caused by TEAK and ORANGE resulted from modifications of the ionosphere. Ionizing radiation from the detonations so disturbed the earth's upper atmosphere that some radio waves were absorbed or scattered.

Riometers (relative ionospheric opacity meters) were operated at Johnston Island, French Frigate Shoals, and Wheeler Air Force Base, Hawaii, on both the TEAK and ORANGE shots. These devices essentially provide a constant measure of the integrated cosmic noise from overhead. Since the cosmic noise pattern is constant from one day to the next, it is possible to detect absorption to an accuracy of better than $\pm$ 1 decibel, by noting depressions in the record. Three frequencies (30, 60, and 120 megacycles) were generally used at each of the three sites to enable absorption to be measured over a wide range.

Echoes from the rising cloud and the resulting aurora were observed on radars during TEAK. Serious absorption was observed by riometers at Johnston Island for hours after the shot, and lesser absorption was observed at French Frigate Shoals and Wheeler Air Force Base.

ORANGE gave numerous echoes long after the shot, although the effects appeared to be less than those for TEAK. Absorption shown by the riometers at Johnston Island lasted several hours.

When altitudes such as that of Shot TEAK are reached, high-frequency communication blackout occurs on some, but not all channels within the affected region. For example, operators working similar frequencies through the same areas experienced markedly different degrees of blackout. Some communications channels were operable at all times. Absorption on the

order of minutes occurs near the shot at even ultra-high frequencies. Clutter from the shot-caused aurora would also be of concern to some radar operations in the general vicinity of the shot, for as long as half an hour.

Ionosonde measurements were also made during the Johnston Island shots to obtain data indicating the effect of a nuclear explosion on the ionosphere and to determine the geographical limits of the effects with time. Measurements were made at French Frigate Shoals, Midway Island, Maui (Hawaii), and from an aircraft. Additional sounding data were obtained from other normally operated Department of Defense ionosphere stations in the Pacific area at Adak and Okinawa. The ionosphere recorder or "Ionosonde" is a radar type device radiating energy directly overhead and recording the returned signal on 35mm film. The record indicates the virtual height in the ionosphere from which radio waves are returned to earth. The frequency used to obtain this reflection is directly related to the ionization at that level.

Results indicated a very disturbed ionosphere following both shots; an area of at least 1500 miles in radius was sufficiently affected by the detonation to disturb some communications, the disturbance being more severe closer to ground zero. TEAK, detonated at the higher altitude, created an intense auroral effect in the direction of French Frigate Shoals, and was accompanied by some increase in absorption. It also created an intense increase in absorption and an apparent decrease in ionization of the F-layer over Maui, Hawaii. After sunrise a moderate increase in absorption was noted at both locations.

After the ORANGE detonation the major effects were delayed until after sunrise, when apparently the sun's radiation caused photo-dissociation of the remaining negative ions. This created a great increase in ionization and absorption of the lower layers of the ionosphere.

Shots TEAK and ORANGE were also observed using two UHF, airborne radars. The radar of lower frequency detected strong returns from both bursts for a period slightly under an hour. The other radar received returns from both shots, but substantially weaker and of shorter duration. Stronger returns were received from the lower altitude shot (ORANGE) at both frequencies. In each case, the development of the returns on the radar scopes indicated three separate periods

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of duration. Little or no return was observed for a period of about a minute. Thereafter, the return built rapidly to strong signals over a wide area that took an oval shape oriented in the North-South direction. This period lasted for several minutes. The final period was characterized by breaking and fading of the return, and sporadic, weak or medium returns from an area oriented along a east-west line somewhat to the north of the actual burst point.

SURFACE OVERPRESSURE MEASUREMENTS

Air blast pressure valves measured near the earth's surface at Johnston Island were insufficient to cause structural damage or break windows.

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GEOLOGIC STUDIES OF UNDERGROUND NUCLEAR EXPLOSIONS RAINIER AND NEPTUNE FINAL REPORT

Thomas L. Thompson and John B. Misz

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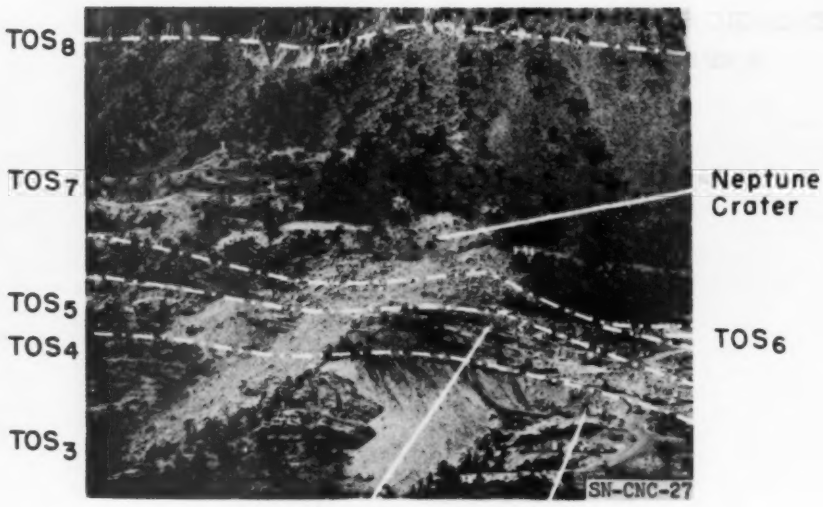

Frontispiece. Above, Aerial View of Rainier Mesa. Below, Neptune Crater, U12-B Tunnel Portal, Core Laboratory, etc.

ACKNOWLEDGMENTS

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The contribution of the United States Geological Survey is evidenced by the basic data in the form of maps and reports that they have published in recent years.[2, 4, 5, 6] Specific thanks are extended to V. R. Wilmarth of the U. S. Geological Survey for his help in familiarizing the writers with the Rainier lithologic subunits.

Grateful acknowledgment is made for the assistance rendered by members of the various agencies involved at the Nevada Test Site. W. G. Flangas and his "B" tunnel mining crews were particularly helpful in the field. This report would not have been possible without the cooperation of members of the engineering and geological staffs at Lawrence Radiation Laboratory, Nevada. Particular reference is made to the illustrations completed by L. Scott Grady. Photography is by Lloyd Guymon and Sam Lauffer. Graphic logs of core analyses were prepared by the LRL-N geological staff, especially J. Skrove and J. McCutcheon. The report has benefited from critical reading and helpful suggestions by R. B. Hoy and R. M. Foose of Stanford Research Institute, S. E. Warner of the Lawrence Radiation Laboratory in Livermore and P. D. Trask of the University of California. Holmes and Narver has supplied survey control for mapping. Drill holes were located by Eastman Survey.

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GEOLOGIC STUDIES OF UNDERGROUND NUCLEAR EXPLOSIONS RAINIER AND NEPTUNE

Thomas L. Thompson* and John B. Misz**

I. INTRODUCTION

This report is an analysis of rock changes and displacements resulting from underground nuclear explosions Neptune and Rainier.

A. Background Information

Rainier and Neptune were exploded at the end of tunnels driven into the side of Rainier Mesa. (See Figs. 1 and 2.) The mesa is capped by 250 feet of hard, brittle, welded tuff (TOS_8). This welded tuff is underlaid by a 500-foot sequence (TOS_7) of pyroclastic materials, which range, generally, from structurally weak, friable materials in the upper two-thirds to compact, hard materials in the lower one-third. This in turn is underlaid by welded tuff (TOS_6) which varies in thickness from 10 feet on the surface near Neptune to 85 feet under Rainier. Beneath TOS_6 is another 600 to 800 feet of bedded tuff which is generally well-cemented and hard. This pyroclastic sequence rests on Paleozoic limestone and dolemite.

The Rainier explosion took place in a $6 \times 6 \times 7$ foot room, 90 feet above the base of TOS_7 and in the bottom of a shallow east-northeast trending syncline. The vertical depth of burial was 900 feet and the distance to the nearest point on the sloping surface of the mesa was 790 feet.

The Neptune shot room measured $12 \times 17 \times 10$ feet high. The shot was located 10 feet above the base of TOS_7 which dips 15 to 25 degrees to the northwest. The vertical depth of burial was 110 feet and the nearest point to the surface was 100 feet.

The total energy release was equivalent to 90 ± 20 tons of high explosives for Neptune and 1700 tons of high explosives for Rainier. One ton is defined as 10^9 calories of energy.

The Neptune explosion broke out to the surface with some venting of radioactive material. Documentary films show the sudden bulging of the mountain side over the detonation point. This bulge expanded and rose to

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a height of 25 to 35 feet at which time the explosion burst out on the downhill side from under the domed mass, and great volumes of rock were blasted some 80 feet into the air and down the mountain side. Sequentially the domed mass settled back into the void with the result that a crater was formed which measures 200 feet wide and 50 feet deep. Open fractures are observed on the surface to a radius of about 150 feet.

The Rainier explosion was completely contained.[1] The main tunnel collapsed to a radial distance of 200 feet from ground zero and spalling was observed to about 400 feet. At 1100 feet from the center of detonation, there was a shift along a bedding plane of about 4 inches. A 9-inch vertical displacement was observed at the ground surface 350 microseconds after the explosion. Rocks were shaken loose from the cap rock (TOS_8) for distances of about one-half mile on each side of the detonation point.

The sequence of events immediately following the explosion as reconstructed by previous workers[1] is as follows:

At the time the energy was released in the shot room, the temperature was about 1,000,000°K, and the pressure 7,000,000 bars. (1 Bar = 1 atmosphere.) The shock for about the first three feet was sufficiently strong to vaporize the rock, and to melt it to a radius of 15 feet. The rock was crushed to a radius of about 130 feet.

As the shock moved outward, the room expanded spherically and reached a radius of 62 feet in several milliseconds. At this time, the cavity was lined with about 4 inches of melted rock (that was initially contained in a sphere of radius 15 feet about the center of detonation), at a temperature of 1200°C to 1500°C. The cavity when first formed was filled with steam at a pressure of 40 atmospheres, which is approximately the lithostatic pressure. The cavity stood long enough, between 30 seconds and 2 minutes, for much of the fluid rock to flow down the sides and to drip from the roof. At this time the cavity began to collapse and cool rapidly due to expansion of the steam which quenched some of the droplets of rock in free fall, as well as some of the "icicles" as they hung from the cavity roof. The cavity was filled with broken rock from the collapse, and the caving progressed vertically to a distance of 388 feet above the point of detonation. Because of the presence of water and the large permeable region produced by the collapsed cavity, the melted rock rapidly cooled to the temperature

of boiling water, 93°C (at elevation 6600 feet). All of the rock which was initially melted converted to a glass on cooling. The glass was found to contain all of the radioactive fission products except some of the rare gases.

The model just described is based on data from one hole (R-6) drilled from the surface vertically downward through the point of the detonation, and from three cored holes (B, C, and D) drilled from within the tunnel. (See Plate V.) Drilling vertically downward revealed no radioactivity until the drill broke into a 25 foot high cavity at depth 513 feet. From this point down to the center of detonation, the rock was broken and permeable as indicated by the failure to recover cores and by the loss of drilling fluid. Drill holes B, C, and D revealed a crushed region within a 62-foot radius from ground zero.

For further details of the phenomena and geologic effects of underground nuclear explosions as understood previously, the reader is referred to reports by Johnson and Violet[1] and Diment et al.[2]

B. Present Study

The principal objectives of the current study are:

1. To determine the present physical distribution and condition of rock materials.
2. To establish the original position of displaced rock materials.
3. To extend the knowledge of the results of detonation of Rainier and Neptune.
4. To establish criteria by which data pertinent to the understanding of the explosions can most readily be derived and described.
5. To relate these studies to practical engineering and mining application.

The method of approach has been to utilize elementary geologic observation of lithologic and structural details and stratigraphic correlation. The data are derived primarily by hand-lens examination of drill core from some 5,000 feet of drilled depth, from surface mapping in Neptune area, and from underground mapping of two 400-foot exploratory drifts in the Rainier area.

The physical and lithologic properties of the rocks in the different stratigraphic units are discussed in detail in Section IV because this information composes the principal factual data upon which this report is based. The interpretations discussed in the text and shown on the illustrations are

based upon factual data and application of the theory of rock deformation. The results of the investigation are illustrated by plans and cross sections (Plates I through VI). The main text is principally a discussion of these illustrations with brief excursions into theoretical aspects and discussion of possible practical application.

II. SUMMARY AND CONCLUSIONS

The approximate physical distribution and condition of displaced and ruptured rock materials in the Rainier and Neptune areas have been established by geologic observation of structural and lithologic details, and stratigraphic correlations. The effects of the detonations are found to be related to the rock types considered from the standpoint of engineering materials as well as to their structural positioning. Gross displacements and fracturing are in apparent accord with Mohr theory of rupture stress orientation. Factual data find explanation on the fundamental basis of primary (blast) and secondary (gravity) induced principal stresses.

The 90±20-ton Neptune explosion disaggregated and displaced rock materials to a radial distance which ranged between 45 and 100 feet from ground zero depending on the orientation of bedding plane weaknesses and proximity of the ground surface to the point of detonation. Primary fracturing extended from ground zero to a radial distance which ranged from 55 feet to an estimated 145 feet depending on the favorable distribution of geologic structural weaknesses. Neptune was found to exhibit primary (blast) and secondary (gravity) rupture features which are fundamentally the same as those found in the Rainier area.

The 1700-ton Rainier shot initially formed a fused-rock-lined cavity of an average 62±10-foot radius below ground zero and an undetermined radius above ground zero. Gross primary rock displacement and grain disaggregation took place to a radial distance of from 80 to 130 feet from ground zero. Visible primary fracturing extended to a radial distance which ranges between 150 and 220 feet depending on the proximity of hard brittle rock (welded tuff) which, it is concluded, transmitted rupture stresses to a much greater distance than the "punky" granular tuff. Collapse of rock material into the initial cavity was favored by primary shear fractures, which developed prominently to a radius of 150 feet from ground zero. The collapsed rock defines

a 100-foot-diameter cylindrical zone. This zone is presumed to extend for 388 feet upward from ground zero. A dome-shaped top is postulated on the basis of Mohr stress theory.[11] It should be noted that, with the exception of drill hole G, there has been no drilling or underground working above the "Raise"Drift. Cavities, distributed around the perimeter of the cylinder, are attributed to variations in the coherence of the rock strata which were disrupted during collapse. The collapse block has remained essentially intact. This fact, coupled with the virtual absence of radioactive fission products above ground zero and nearly complete pulverization of the central collapse block, leads to the conclusion that underground nuclear explosions are applicable to mining by block-caving methods. Furthermore, material within the crushed zone should be mineable without the use of additional explosives. The mineability of material within the fracture limit is a question that is difficult to answer at present, as the degree of fracturing has not been established. Perhaps the direct approach of experimental excavation would be the best solution to the problem.

The conclusions enumerated above should be considered as hypotheses awating verification. There is still much to be learned from the Rainier explosion.

III. WORK PROCEDURES AND FACTUAL DATA

Methods of analysis are discussed in relatively great detail for the possible benefit of other persons who may be engaged in this type of work. As the methods of core logging and data presentation to-date are in the developmental stage, minor inconsistencies are to be expected. All maps, graphic core logs, plans and cross sections have been completed at the same scale (1 inch: 20 feet) to allow convenient analysis. Observed details are given on field maps and in written descriptions of field observations and core analysis. Core logging data are in graphic form to aid interpretation. Plans and cross sections have been developed from and concurrent with the collection of basic data.

A. Surface Mapping

Surface geologic and topographic maps were prepared in the Neptune area using plane table and alidade methods. All rod stations were located directly from the same instrument station, 125 feet east of ground zero.

The reader is referred to Plate I for details of the mapping. Large boulders within the boundaries of the rubble area are drawn to scale.

B. Tunnel Mapping

With the exception of a brief examination of U12.03-C drift, the authors' tunnel mapping was confined to the Rainier area. Plan mapping was carried out at waist level with steel tape measurements between surveyed drift station numbers. Cross sections of the walls were mapped where significant details were not found in plan.

In U12-B "Raise" Drift, mapping was conducted concurrently with mining activity by daily or twice daily trips to the heading. This procedure was considered essential for adequate mapping of the drift as wall lagging and overhead spiling have since concealed many of the pertinent geologic details.

The U12-B Exploratory Drift was mapped for obvious geologic features and some further geologic detail was obtained from USGS-TEI Report 355.[2]

C. Core and Core Hole Analysis

Core and core hole investigation included analysis of radiation measurements, drilling data, rock fracturing, petrographic descriptions, and other pertinent observations.

Cores were examined from 13 drill holes totaling 3100 feet of drilled depth in Rainier area, and 11 drill holes totaling 1800 feet of drilled depth in Neptune area.

1. Rock Descriptions.

Petrographic descriptions were by hand lens examination with basic reference to color, structure, hardness, and texture. Structure is referenced with terms such as massive, thick-bedded, etc.

An arbitrary hardness scale was set up on the basis of numbers from 1 to 5. The numbers in sequence refer to the rock as (1) loose or slightly cemented grains; (2) friable when the rock can be readily disintegrated by hand; (3) slightly friable when grains may be rubbed off with the fingers but the material does not disintegrate; (4) hard when the material is broken by hand with difficulty; (5) very hard when the material is silicified or cherty.

Texture refers to size, shape, percentage, and distribution of mineral and rock particles. Colors represent the general color of samples rather than the color of individual particles or fragments, which are

specifically described. In some instances, colors have been keyed to the rock color chart as developed by the Geological Society of America (1951).[14]

Rock names for pyroclastic rocks are based on the dominant particle size. The Wentworth scale as presented by Wahlstrom[3] is used with the exception that the term medium tuff is added. The terminology is presented as follows:

Fragment type	Size	Rock type
Block, bomb	Over 32 mm	Volcanic breccia or agglomerate
Lapilli	4 to 32 mm	Lapilli tuff
Coarse ash	2 to 4 mm	Coarse tuff
Medium ash	1/2 to 2 mm	Medium tuff
Fine ash	Less than 1/4 mm	Fine tuff

2. Core Examination.

Core descriptions are as described from wet samples. Preliminary examination of cores was made at the drill site when possible. Subsequently, the core for the entire drilled depth was laid out in sequence in the laboratory. A cursory examination was made by breaking and wetting the core and leaving the freshly broken end face-upward in the core box. Stratigraphic contacts were picked and general notes made on such things as fused fragments, wood debris, crushed materials, and the degree and type of fracturing. The angle between bedding and core axis was determined by protractor with the core held parallel to the core box. Representative samples were selected of the different lithologies and the samples were examined with a hand lens to obtain petrographic details. These samples were subsequently cleaned and coated with clear plastic to simulate wetting. The samples are kept on file for correlation and reference purposes.

3. Data Analysis.

Factual observation and interpretation were initially recorded in long hand. Subsequently, the data on core logging, drilling, and radiation were combined on graphic logs at a scale of 1 inch: 20 feet. At the top of each page the map coordinates, elevation, inclination, and bearing

are given for the beginning of each one hundred feet of drilled depth. The common parameter, hole depth, allows ready comparison of the various types of data.

D. Illustrations

Basic data, as discussed in preceding paragraphs, have been plotted to scale (1 inch: 20 feet) in plan view and in two cross sections for each explosion area. Symbolic representation of basic data is used to conserve space and make interpretation easier. The legend included with each illustration explains the various symbols. Lithologies are represented both for stratigraphic analysis and for evaluation as engineering materials.

IV. STRATIGRAPHY AND ENGINEERING MATERIALS

Neptune and Rainier were exploded within a 2000-foot sequence of moderately folded (maximum dip 35°) and faulted Tertiary pyroclastic rocks which overlie Paleozoic limestones and dolomites.

The pyroclastic sequence, which is referred to as the Oak Springs Tuff (TOS) by Johnson and Hibbard,[4] has been divided by Hansen and Lemke[5] into eight units referred to as TOS_1, TOS_2, etc. These units have, in part, been divided into subunits which have been given letter designations by Gibbons[6] in the Rainier area. These letter designations for TOS_6 and TOS_7 have been maintained by Diment et al.[2] in their analysis of the Rainier event. The letter "Z" was used for the highest stratigraphic unit exposed in the Rainier underground workings. It is apparent that, in order to extend the subunit designation stratigraphically upward, a new system must be adopted. Accordingly, subunits in each area are given number designations beginning with 1 at the base of each TOS unit. Since lithologies vary considerably from area to area, a small letter suffix (denoting the area) is included with each subunit number. Thus the basal subunit of TOS_7 in the Neptune area is referred to as $TOS_{7\text{-}1n}$. In the Rainier area, a capital letter is included in parentheses to reference the U. S. Geological Survey letter system.

A. Neptune Stratigraphy

Dips of bedding in the Neptune area vary from 35° to 10° (Plate III). Lithologic units TOS_5, TOS_6, and the lower part of TOS_7 are pertinent to an understanding of the explosion effects. In section A-A' (Plate II), the preshot stratigraphic contacts have been reconstructed from core data obtained from apparently undisplaced rock.

The basal 230 feet of TOS_7 is included in a stratigraphic sequence which was measured, sampled, and described on the surface west of Neptune crater. Tape and compass were used for detailed measurements with thickness control by plane-table and alidade. Sample stations are located by number on Plate I. This 230-foot sequence was divided into 10 subunits designated as $TOS_{7\text{-}1n}$, $TOS_{7\text{-}2n}$, etc. These units were projected along strike to the line of Neptune cross section B-B' (Plate III). Preshot stratigraphic contacts in this section were then reconstructed on the basis of the projected surface contacts, cross section A-A' preshot contacts, and data from core holes in the vertical plane of cross section B-B'. Lithologic units thus established were measured for thickness, and a composite stratigraphic column was described on the basis of core analysis and surface sample description. Likewise, the upper part of TOS_{5n} and TOS_{6n} were defined. A description of these units is included in subsequent paragraphs and in brief on Plate I. U. S. Geological Survey descriptions were adopted for TOS_{4n} and the lower part of TOS_{5n}.

Unit TOS_{5n} (thickness 100 to 125 feet), is greenish gray, yellowish gray, olive green, and brown; fine-to coarse-grained; slightly friable to very hard lapilli tuff, which generally forms ledges at the ground surface. Pumice fragments are typically elongated and flattened, while lithic and obsidian fragments up to 15 mm in diameter are scattered throughout the section. The upper 15 feet of the unit are composed of greenish orange, massive, slightly friable; low density; porous lapilli tuff. Greenish gray and orange pumice lapilli range in size from 5 to 15 mm in diameter. Dark green to black, low density, brittle, devitrified obsidian lapilli commonly compose 5% of the rock. 4- to 10-inch interbeds of coarse sandstone make up about 10% of this interval. The top few feet are commonly white to light gray, fine, earthy material believed to be the result of baking during deposition of the overlying welded tuff.

Unit TOS_{6n} is composed of dark purple, yellowish green and brown, very hard, fine tuff and agglomerate with 5 to 20% dark lithic fragments from 1 to 15 mm in diameter, and with a few percent of large (4 to 20 mm), partly flattened pumice lapilli. The top few feet of the unit are typically orange brown to hematite red, fine, earthy material. Examination of Plate III reveals that this unit thickens northwestward from 10 feet to 40 feet in a horizontal distance of about 300 feet.

Subunit $TOS_{7\text{-}1n}$ (thickness 1 to 3 feet) is light yellowish green, wavy bedded, slightly friable, lapilli tuff with 5 to 30% dark angular lithic fragments

5 to 20 mm in diameter. The upper contact of the subunit is gradational with the overlying sandstone.

Subunit TOS_{7-2n} (thickness 12 to 15 feet) is primarily a brown, cross-bedded, hard to slightly friable, fine-grained sandstone. The lower few feet of the unit typically contain 1/4 to 3-inch interbeds of yellowish white lapilli tuff (gradational into underlying unit) and lavender brown claystone with 30% light greenish yellow pumice fragments 1 - 3 mm in diameter. The unit grades over a 3-foot zone into overlying subunit TOS_{7-3n}.

Subunit TOS_{7-3n} (thickness 8 to 12 feet) is a buff to light brown, massive, hard to slightly friable, coarse tuff with 5 to 10% yellowish gray to pink tuff lapilli from 4 to 15 mm in diameter. The subunit is gradational into underlying subunit TOS_{7-2n}, the contact being picked where volcanic material predominates over fine sand. Irregular (scalloped) patches of reddish orange porcellanite are common near the base. The upper part of the subunit generally is porcellanite (commonly with faint outlines of lapilli-size fragments), but varies in color from chalky white to brick red or reddish brown.

Subunit TOS_{7-4n} (thickness 20 to 25 feet) is composed of light gray, greenish gray and yellowish gray pumice lapilli (4 to 20 mm in diameter) which form a massive, hard to slightly friable, low density, porous rock with 0 to 5% of dark, angular lithic fragments. This subunit commonly contains interbeds (up to a few feet thick) of brown, sandy tuff typical of subunit TOS_{7-5n}; however, a distinction can be made on the basis of associated pumice lapilli which are gray and gray green in TOS_{7-4n} and white or pink in TOS_{7-5n}.

Subunit TOS_{7-5n} (thickness 20 to 25 feet) is brown, massive, hard to slightly friable, fine to medium grained, sandy tuff with 5 to 15% light yellow to white pumice lapilli from 4 to 15 mm in diameter. The upper few feet commonly show conspicuous fine red specks.

Subunit TOS_{7-6n} (thickness 10 to 15 feet) is typically composed of gray and brown, hard to very hard (silicified), medium-grained sandy tuff. The interbeds seem to vary in thickness along strike. The following sequence was measured and described on the ground surface northwest of Neptune crater (see Plate I).

Bottom: 4 feet (sample 9) of gray, massive, hard, medium-grained, sandy tuff with conspicuous (15%) black mineral fragments (biotite and hornblende).

4 feet (sample 10) of brown, massive, hard, fine-grained, sandy tuff.

Top: 2 feet (sample 11) of mottled gray, very hard (silicified), lapilli tuff.

Total thickness - 10 feet (approximately).

Subunit TOS_{7-7n} (thickness 50 to 60 feet) is slightly friable to friable, thick bedded (1 to 7 feet), medium-grained tuff. Massive beds grade from gray at the bottom to light brown at the top. Two feet from the top of the unit a 6-inch interval is dominated by bluish gray pumice lapilli (4 to 15 mm in diameter). The following sequence was measured northwest of Neptune crater.

Bottom: 18 feet covered.

8 feet (sample 12) of thick beds (2 to 4 feet) which grade from gray, friable tuff at the bottom to light brown, friable tuff at the top. The interval contains occasional 4-inch-diameter, brown, silicified, "rock-ball" concretions. (See Fig. 3.)

6 feet (sample 13) of massive, medium-grained tuff, which grades from gray at the bottom to brown at the top.

6 feet (sample 14) of friable, medium-grained, sandy tuff in 1- to 2-foot beds which grade from gray at the bottom to brown at the top.

7 feet (sample 15) of gray to brown, poorly bedded, friable tuff, with some pink lapilli and a 6-inch fine, lightweight tuff bed at the base.

4 feet (sample 16) of brown, massive, friable tuff. The interval is gray in the bottom half, with an irregular distribution of pink lapilli. Two feet from the top of the sequence bluish gray lapilli and 10% lithic fragments dominate a 6-inch thickness.

Top: 1 foot (sample 17) of gray, friable, lapilli tuff with a dominant pink color at the top.

Total thickness - 50 feet (approximately).

Subunit TOS_{7-8n} (thickness 20 to 25 feet) is brown, massive, slightly friable to friable, medium- to coarse-grained, tuffaceous sandstone and sandy tuff with 0 to 5% white pumice fragments (3 to 10 mm). The base of

this unit is recognized by a 30-inch interbedded (4 to 8 inch) sequence of: (1) Lavender brown, faintly bedded, hard, fine-grained tuff (sample 18-1) with 0 to 5% white pumice fragments (1 to 10 mm). (2) Mottled brown, friable, medium tuffaceous sandstone (sample 18-2) with 10% white to blue-gray pumice lapilli (4 to 20 mm).

Subunit TOS_{7-9n} (thickness 20 to 25 feet) is massive, friable, fine- to medium-grained tuff in 2- to 6-foot beds which grade from gray at the bottom to light brown at the top.

Subunit TOS_{7-10n} (thickness approximately 30 feet) is gray to buff, poorly bedded (6 inch to 3 feet), hard, fine- to medium-grained tuffaceous sandstone.

B. Rainier Stratigraphy

The Rainier shot chamber was in the bottom of a shallow east-northeast trending syncline in which the dip within the area of study approaches a maximum of 12 degrees on the south flank. Although an approximate correlation is apparent between the Neptune and Rainier areas, the variations are sufficient to warrant separate descriptions. Descriptions by the U. S. Geological Survey have been incorporated and extended.

In contrast to the Neptune area, drill holes below Rainier ground zero reveal TOS_{5r} as a hard, brittle tuff, while TOS_{6r} is a massive, 85-foot thick, hard, welded tuff with 20 feet of black obsidian at the base. (See Fig. 2.) It seems probable that the light-weight, porous lapilli tuff, typical of the Neptune area, has been baked by the deposition of TOS_{6r} and considerably compacted by this and overlying materials. The change in thickness of TOS_6 from 20 feet in the Neptune area to 85 feet in the Rainier area (a horizontal distance of 1200 feet) is not so surprising if one considers that this material originated as a fluidized mass of incandescent gas and ash moving swiftly out from its source. The "lens" of black obsidian at the base of TOS_{6r} perhaps represents a rapidly cooled "forerunner" to the welded tuff.

Subunit TOS_{7-1r} (Q) is as described for Neptune area.

Subunit TOS_{7-2r} (R) persists as a cross-bedded sandstone, but thickens to a maximum of 40 to 50 feet in the Rainier area.

Subunit TOS_{7-3r} (S), (thickness 10 to 13 feet), is buff, massive, friable to slightly friable, coarse tuff. Light gray and yellowish gray to pink lapilli (4 - 15 mm diameter) constitute approximately 10% of the unit. The base is recognized by the presence of irregular, "scalloped" patches of reddish orange porcellanite.

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Subunit TOS_{7-4r} (T, U, V_1, V_2), (thickness 18 to 20 feet), is typically gray to greenish and yellowish gray, slightly friable, lightweight, porous, lapilli tuff with 5% dark angular lithic fragments (4 to 20 mm in diameter) and occasional 6-inch to 1-foot interbeds of reddish brown, sandy tuff. The basal few feet (up to 8 feet) of this unit are usually composed of chalky white silt and clay size material believed to result from devitrification of lapilli tuff. Lapilli-size grain outlines are commonly observed on close examination. About 3 feet from the top of the subunit is a 6-inch interbed of hard, conglomeratic porcellanite which persists as a "marker" bed throughout the U12-B tunnel area. In the U. S. Geological Survey system, this bed marks the base of subunit V; however, the overlying 3 feet of greenish gray pumice lapilli tuff are lithologically similar to subunit U but in sharp contrast to subunit V. The contact between TOS_{5-4r} and TOS_{5-5r} is therefore placed at the top of the greenish gray lapilli tuff.

Subunit TOS_{7-5r} (V_3), (thickness 25 to 30 feet), is brown to pinkish brown, massive, hard, fine, sandy tuff, with 5 to 15% (locally 30%) pale yellow to greenish yellow pumice fragments 4 to 12 mm in diameter.

Subunit TOS_{7-6r} (W_1, X, Y, and Z), (thickness 10 to 15 feet), is composed of 1- to 4-foot interbeds of: (1) Greenish to dirty-gray, massive, hard, sandy tuff, with up to 30% lithic and mineral fragments. (2) Brown, hard, fine, sandy tuff, which has up to 10% light yellow tuff fragments.

Subunit TOS_{7-7r} (thickness 70 feet) in cores from drill holes G and R is predominantly light brown to grayish brown, massive, hard, fine- to medium-grained, sandy tuff with 10% of 1- to 3-mm diameter white tuff fragments and occasional 1- to 2-foot interbeds of silicified material which contains up to 80% pumice lapilli. Gray, fine- and medium-grained tuff interbeds make up about 10% of the subunit. In the upper few feet, the sequence grades to a brown, slightly friable sandy tuff which has occasional mottled green porcellanite nodules up to 2 feet long and 6 inches thick.

Subunit TOS_{7-8r} (thickness 40 feet) is typically friable to slightly friable, medium-grained, sandy tuff with 2- to 7-foot beds which grade in color from gray at the bottom to brown at the top. White and pink pumice lapilli compose 5 to 30% of the rock with local concentrations as high as 50%. The unit typically contains 6-inch to 1-foot-thick porcellanite lenses from a few feet to 30 feet in length. These lenses grade laterally to lapilli tuff and are believed to be the result of silica deposition by groundwater percolating through

the porous beds. "Rock-ball" concretions from 3 to 9 inches in diameter are also typical of this interval. At the top of the subunit is a 10-foot-thick, pale olive to pinkish tan, massive, slightly friable, fine tuff which contains from 10% to 50% pink, blue-gray, and white pumice lapilli. This unit is recognized in drill holes I-2, J-2, and K and is present in large collapse blocks between stations 3 + 35 and 3 + 45 in the "Raise" Drift.

Subunit TOS_{7-9r} is at least 55 feet thick as observed from I-2 drill cores. The lower 30 feet of the unit is brown,thick-bedded to massive, friable, sandy tuff or tuffaceous sandstone. Above this is a 25-foot-thick interbedded (2 to 5 feet) sequence of light greenish gray, slightly friable, lapilli tuff; and medium to coarse, yellowish brown, massive, friable tuffaceous sandstone. The subunit, as described above, is correlated with materials exposed in the "Raise" Drift between stations 2 + 00 and 3 + 30. However, the light colored interbeds here are light gray to chalky white, fine tuff. The conclusion is reached that the lapilli-size fragments as observed in core from the I-2 hole have been pulverized during collapse of the material from 70 feet above. Distortions of this material as shown in Figs. 17 and 18 are offered as concluding evidence for pulverization. The basal few feet of the sequence, as exposed in the Exploratory Drift, are light tan, thin-bedded to massive, fine tuff, which, between station 3 + 20 and 3 + 30, contain up to 50% dark angular chert (volcanic) gravel. This gravel was also recognized in material recovered from drill hole K-2.

The base of subunit TOS_{7-10r} is seen at station 2 + 60 in the "Raise" Drift where large blocks (up to 3 feet in diameter) of brown, massive, slightly friable, very coarse, pebbly, tuffaceous sandstone are exposed. The rock has 5% of white pumice lapilli (5 - 15 mm in diameter). Brown sandy tuff and tuffaceous sandstone answering this description is observed in G hole cores from a depth of 221 to the total depth of 551.8 feet. Four-foot interbeds at depths of 400 and 418 feet are light bluish to greenish gray, massive, lightweight, friable, fine to lapilli tuff. The thickness of subunit TOS_{7-10r} has not been defined.

C. Engineering Materials

The rocks described in the preceding paragraphs may, from a geological engineering standpoint, be divided into four types as follows: (1) Hard, brittle rock, which would include welded tuff, porcellanite (silicified or devitrified tuff) and such very hard granular tuffs as TOS_{5r} and TOS_{7-7r}.

(2) Compact to friable rock, which would include the indurated granular tuffs in the lower part of TOS_7; units TOS_1, TOS_2, TOS_3; and sandstones such as TOS_{7-2}. (3) Structurally weak rock which would include the friable, granular tuffs which extend stratigraphically above TOS_{7-6r} and TOS_{7-7r} to the base of TOS_8. (4) Porous, compressible rock, which is typified by the lightweight lapilli tuffs of TOS_{5n} and TOS_{7-4n}, and to some extent by TOS_{7-4r}.

For more detailed and varied discussion of the Oak Springs Tuff relative to its engineering properties, the reader is referred to report UCRL-5542 by Warner and Violet.[7]

V. DISCUSSION AND INTERPRETATION

From a structural geologist's point of view, the effects of underground nuclear explosions may be thought of in terms of the stress origin. On this basis, effects are divided into primary (blast) and secondary (collapse) features, depending on whether the explosion or the force of gravity imparted the dominant stress.

The blast (primary) features may be categorized in terms of an initial cavity, a crushed zone and a fractured zone. Secondary (collapse) features are referred to in terms of fracture limit and central collapse block. Both explosion and collapse stresses are considered in the concept of a main shear zone.

A. The Initial Cavity

The Rainier shot obviously had an initial cavity which was lined by fused rock. Dark green to black and brown, highly radioactive, vesicular fused material was observed continuously in cores over drilled distances which range from 3 to 10 feet in holes B, C, H, I, J, K, and T-11. This material is distributed in a hemispherical shell below ground zero at an outside radial distance which ranges between 55 and 75 feet (see Plate V). An average 62 $\pm$ 10-foot radius for the initial cavity is evident. The thickest concentration of glass was along the bottom of the cavity, as indicated in drill holes H and T-11. Light brown tuff immediately overlying the fused core is part of the lithologic subunit TOS_{7-7r}, which existed above the shot chamber prior to detonation. Little or no fused core was observed in holes I-2, J-2, and K-2 which were drilled up from the Exploratory Drift alcove. A fused fragment

at a depth of 75 feet in I-2 (65 feet from ground zero) appears to be near the former cavity boundary. Fused fragments, as shown in Figs. 3 and 4, are distributed through TOS_{7-7r} adjacent to the fused core and also in sections of drill hole D (see Plate V). These are presumed to have been emplaced in the rock which formed the ceiling of the cavity.

The hemisphere of fused glass in Rainier, according to Kennedy and Higgins,[8] has resulted from direct melting plus additions by flow down the sides of an initial cavity. Flow structures observed by Donald Rawson (personal communication, November 24, 1959), in a study of thin-sections, tend to support this conclusion. Nevertheless, the positioning of the fused material as shown in Plate V suggests that some of this glass concentration may be attributed to preferential melting of a specific rock type, (in this case TOS_{7-6}). This possibility could be easily evaluated by laboratory tests.

B. The Crushed Zone

A crushed zone is defined by the limit of obvious grain disaggregation and gross primary displacement of rock materials. Wood fragments and the pulverized and crushed appearance of drill cores offer clues to the extent of the crushed zone. Physical displacement and obvious thinning of stratigraphic units are apparent in both the Neptune and Rainier areas.

The crushed zone thus defined is observed to extend (in the Rainier area) for a radial distance of some 80 to 100 feet, with a maximum extent of 130 feet, southeastward from the shot point. The anomalous extent of crushing in this direction probably can be attributed to the fact that the preshot drift extended in this direction. As noted in the Introduction, this drift collapsed to a radial distance of 200 feet. The disturbed and jumbled materials observed on the northeast wall of the Exploratory Drift at stations 16 + 25 (Fig. 7) and 17 + 50 are tentatively assigned to TOS_{7-6}. Radiation measurements made on both sides of the fused stringer (Fig. 7) showed high radiation in the direction away from the shot point (right) but low radiation toward the shot point. The conclusion was reached that the stringer marked the boundary between collapse material on the ground zero side and crushed material on the side away from ground zero.

Measurements of bulk density, grain density, porosity, permeability and compressive strength as quoted by Warner and Violet[7] from work by Diment et al.,[15] and measured along the Exploratory Drift, show anomalies

which appear to be related to the crushed zone (Plate V). Measurements of compressive strength suggest that crushing extended to a radial distance of 100 feet from ground zero. Permeability increases toward ground zero abruptly at station 16 + 00 (80 feet from ground zero) from about 1.5 millidarcies to more than 14 millidarcies. At station 16 + 30 (60 feet from ground zero), bulk density decreases from about 2.2 to 1.8 g/cm^3, and porosity increases from 20-30% to 30-44%. A comparison of postshot measurements with preshot measurements indicates that the grain density of subunit TOS_{7-5r} (V) has been reduced. Apparently grain disaggregation has resulted in a looser packing. Dry bulk density determinations tend to support this conclusion. Analysis of thin-sections as described in a subsequent paragraph relative to the properties of the fractured zone also tend to delineate the limit of crushing.

Drilling above ground zero in the Rainier area has not been designed to delimit the extent of crushing. Furthermore, analysis of crushing in this direction is complicated by secondary (collapse) features.

In the Neptune area, crushing extends downward about 40 feet and laterally about 50 feet, except in the southeast direction (Plate III) where crushing effects are observed to a radius of at least 80 feet. A peculiar wave structure is shown in the distribution of TOS_6, TOS_{7-1} and TOS_{7-2} in drill holes A, I, and K. A piece of wood core from a depth of 97 feet in hole K is presumed to have come from the drift which crossed the line of fire at a radial distance of 45 feet. The anomalous extent of crushing apparently was favored by bedding plane weaknesses.

C. The Fractured Zone

Fracture limits include primary as well as secondary effects. A variety of criteria have been used to define the limits as depicted in Plates I through VI. In general, these limits are consistent with marked changes in drill fluid loss, core recovery, or degree of fracturing as interpreted from the graphic logs of the core hole analysis.

Interpretation from cores is immediately confronted with the problem of separating explosion fracturing from preshot and drilling effects. Preshot fracturing can normally be distinguished by some degree of weathering or cementation, but separating explosion fracturing from drilling effects is more difficult.

The peculiar type of irregular longitudinal fracture pictured in Fig. 8 is believed to be a primary (blast) feature. The irregular nature of these fractures leads to the conclusion that they are the result of tensional stresses. It is difficult to visualize how tensional stresses could be thus developed by drilling operations. Such fractures are interpreted as tension cracks resulting from primary stresses directed radially from ground zero.

In the Rainier area, a pronounced bulge in the fracture limit to the southeast is defined by data from drill holes B, C and D (Plate V). This is consistent with the anomaly in the crushed zone and here again is attributed to the location of the Rainier main drift. Support for this fracture limit is found in studies reported by Warner and Violet:[7]

"In specimens from the first 95 feet (stations 14 + 65 to 15 + 60) of the exploratory tunnel, the effect of the explosion is indicated by the closer spacing of the joints in the rock. From 15 + 60 (120 feet radially from the chamber) toward the face, the rock becomes progressively more friable and much of it can be crushed easily in the hand. On drying in air it becomes somewhat more coherent but disintegrates rapidly upon contact with water. A series of half-inch pieces of the brownish tuff from the samples collected along the tunnel were dried in air and then placed in water. Those pieces from samples obtained between 140 and 210 feet from the chamber showed selective disintegration of small masses of white material that apparently are richer in clay minerals. Those pieces from 75 to 120 feet from the chamber showed progressively more disintegration, and those from 65 to 75 feet disintegrated completely within a few minutes to heaps of granular material, mostly smaller than 1-mm diameter. Similar pieces of air-dried lumps of the white tuff from about 140 feet radially from the chamber all disintegrated rapidly in water, possibly due to high content of clay."

Thin-section studies[2] (as quoted by Warner and Violet[7]) further define the fracture zone:

"Under the microscope, thin-sections of the samples from the interval 140 to 210 feet radially from the chamber do not appear noticeably different from the normal preshot tuff of this portion of the Oak Springs formation. A sample at 15 + 50 (130 feet from the shot chamber), however, shows a few short irregular hairlike fractures filled with fine-grained, opaque material. Specimens taken at points further down the exploratory tunnel

contain similar hairlike cracks in progressively greater abundance, and about 75 feet from the chamber they form a fine anastomosing network. In many specimens these cracks show random orientation, in others a single direction may be dominant. Autoradiographs did not show these fracture networks to be appreciably more radioactive than the intervening rock material. In addition to the hairlike fractures, there are scattered thicker masses of this opaque material in the rock in and near the heading of June 6, 1958 (16 + 30). These masses are generally wormlike, up to 1 mm thick, and have blunt or tapering ends. Further investigation of these features are necessary."

To the northwest, the fracture limit is placed near the end of the Exploratory Drift since fractures observed in the walls of the drift seem to die out at about this point. The lateral extent of the fracture limit in Plate VI is largely hypothetical as control data is scanty.

The extension of the fracture limit to a radial distance of 220 feet below the point of detonation is based primarily on the observation of tension fractures in core from hole H (see Fig. 8). Perhaps the greater extension of fracturing in this direction finds explanation in the proximity of the hard, brittle rocks of TOS_{6r} and TOS_{5r}. These rocks, as might be expected, apparently were able to transmit the shock waves to a much greater distance. This conclusion, if verified, could have tremendous practical significance in the planning of future underground detonations in other materials, such as limestone, dolomite, or granite, for these rock types should be expected to behave in a similar way.

In the "Raise" Drift, fractures at station 1 + 85 and between stations 3 + 30 and 3 + 85 as shown on Figs. 9 through 15 are attributed to primary shear. There is little doubt that the most recent movement has been due to collapse of material into the primary (blast) cavity. Nevertheless, the exactness with which these fractures are consistent with expectable shear fractures resulting from radial projection of stress from the explosion point forces the conclusion that they are primary features. In accordance with stress ellipsoid theory, the fractures are inclined at an angle of less than 45° to the principle stress. For strict correspondence with observation, a coefficient of internal friction (ϕ angle) of 40° is postulated and represented in the stress ellipsoids shown on Plates V and VI. Perhaps this ϕ angle value

may seem too high; however, under the extreme temperatures and pressures expectable in these regions, the material may well be expected to behave other than as in the laboratory. It is also observed that the postshot joints between stations 1 + 50 and 1 + 55 are consistent with the postulate.

The fracture limit above the "Raise" Drift in the Rainier area is believed to be defined by the boundary of collapse of material into the central cavity. The boundaries as shown on Plates V and VI are consistent with analysis of core and drilling data from holes G, I-2 and J-2. Bedding dips consistent with preshot structure are particularly conclusive in fixing the approximate limit. Fractures on top of Rainier Mesa as illustrated in Figs. 21 and 22, and located in Fig. 23, are attributed to slumping toward the mountain front along a preexisting gravity shear zone which was reactivated by explosion shock waves. This shear zone forms a 50-foot-wide topographic low in which the soil cover is observed, in the field, to have settled a foot or two below the large rock masses. The former position of the soil mantle relative to the rock masses is shown by a well-defined line below which the rocks were buried.

On the ground surface over the detonation point no fractures were found which could be attributed to collapse into the initial cavity.

In the Neptune area, the fracture limit below the elevation of ground zero is defined principally on the basis of fracturing observed in core analysis. Above the elevation of ground zero, the fracture limit is, in part, related to primary (blast) effects and in part to secondary (gravity) effects.

In the southeast direction (Plate III), primary fracturing is believed to have propagated all the way to the ground surface along the lithologic contact between TOS_5 and TOS_6. As shown in Fig. 25, the hard, brittle TOS_6 unit has been shattered while the compressible, "punky" TOS_5 has remained intact.

Primary breakthrough to the ground surface in the southeast direction, as shown by the documentary film described in the Introduction, probably is related to the favorable dip of the bedding and to the proximity of the detonation to the ground surface. The dominance of rock rubble from TOS_7 subunits 4n, 5n, and 6n as shown on Plate I confirms the positioning of the breakthrough.

The fracture limit to the northwest and southwest of the shot point, as defined by open surface fractures, is believed to be the result of normal

faulting toward the crater created by the blast. Displacements, slickensides, and dips on faults southwest of the shot point (exposed in road cut) are consistent with shearing due to a vertical principal stress (force of gravity).

Northeast of the Neptune shot point, the origin of the fracture limit is confounded by the transition from primary (blast) fracturing to secondary (collapse) fracturing.

D. The Central Collapse Block

There is no doubt that a large mass of rock material was moved by the force of gravity to fill an initial cavity formed by Rainier explosion. The manner of this movement and the source of present distribution of displaced materials will now be discussed.

Perhaps, intuitively, one may picture a jumbled mass of rock types in the central collapse zone. Additional thought should lead to the conclusion that each particle of rock is under the influence of the same force of gravity and should thus be accelerated at the same rate, barring boundary effects. From a theoretical point of view, then, one should expect gravity-displaced rock masses to remain essentially intact at least in the gross sense. This prediction has been conclusively borne out by factual observations.

A brief excursion through the Rainier Exploratory Drift discloses the fact, with one exception, that the material is all of the same lithologic type. Fracturing and somewhat erratic tilting of bedding planes (recognized by textural variations) as shown in Figs. 5 and 6 are observed, but even here, the dips, in general, are toward ground zero.

An apparently anomalous block of rock about 10 feet square rests adjacent to the drilling alcove at station 16 + 84. (See Plate IV.) Well defined bedding strikes N 25° E and dips 30° NW. The block is composed of massive, gray, slightly friable sandy tuff with 1- to 6-inch interbeds of silicified, brown lapilli tuff. The block is apparently surrounded by massive, very light brown, friable, fine tuff which is correlated with the similar but harder materials of TOS_{7-7n} as observed in cores from the drill holes R and G. The lithology of the foreign block is similar to that observed near the base of TOS_{7-8n} as exposed in the "Raise" Drift. The conclusion is reached that this block has been displaced about 100 feet by gravity collapse. Its silicification apparently allowed it to remain intact and to be engulfed by the pulverized materials of TOS_{7-7n}.

The approximate position of the displaced contact between TOS_{7-7n} and TOS_{7-8n} is delimited by pieces of silicified lapilli tuff recovered from drill holes I-2, H-2 and K-2.

By careful mapping and observation in the "Raise" Drift, it has been possible to correlate lithologies from one side to the other of the central collapse block. Figures 9 through 19 show that the originally flat-lying strata have been tilted to high angles and made to flow and slip. Still, only minor mixing is observed. Blocks of coarse, pebbly, tuffaceous sandstone, as observed at station 2 + 60 (directly over ground zero), have been recognized nowhere else except above the "Raise" Drift in drill hole G. It is concluded that here again the rock has collapsed essentially as a unit.

Cavities have been observed, as depicted on Plate V, over the Rainier "Raise" Drift at stations 2 + 00 and 2 + 60. A percussion probe hole (see Fig. 20) defined a void at least 10 feet in diameter 35 feet above the drift at station 3 + 10. A cavity at elevation 7002 feet had previously been encountered by drilling (hole R-6) vertically down from the surface.

Although not conclusive (because of the small number of observations), the positioning of these cavities suggests that more of them may be distributed around the perimeter of a vertical cylinder with a 50- or 60-foot radius. Perhaps such positioning of voids may be attributed to boundary effects of the central collapse block shearing away from the solid rock wall.

A distribution of cavities vertically over ground zero is also indicated. This positioning of cavities, perhaps, is to be expected since it is in the location of maximum subsidence.

The height of collapse above ground zero is a question deserving consideration. The hypothesis is advanced that collapse would progress upward until such time as enough cavities and sufficient increase in bulk porosity had been produced to account for the initial void created by the explosion. It seems self-evident that the bigger the initial cavity the higher would be the collapse. The only factual evidence to date would place the collapse limit (fracture limit) at the top of the cavity detected at the 7002-foot elevation. The dome shape at the top of the collapse limit is predicted on the basis of expectable distribution of principal stresses. It is interesting to draw an analogy to stress distributions as predicted by Anderson and Jeffreys[9] in their analysis of the stress conditions which prevail in the formation of certain natural geologic features (cone sheets, ring dykes, and

caldron subsidence). Billings[10] also has developed theories along these lines.

The strength of materials in and above the central collapse block is pertinent to block caving considerations. The flow features shown in Figs. 17 and 18 certainly indicate that this material is not strong structurally and should be expected to collapse under its own weight with very little agitation. That the material in the collapse block is unstable is supported by the fact that solid roof spiling and wall lagging were required through the total traverse of the central collapse block in the Rainier "Raise" Drift. There was serious doubt as to whether the drift was feasible when pulverized rock engulfed the heading at station 2 + 00. Without the benefit of expert mining techniques, the drift could not have been completed.

The instability of the material overhead was continually in evidence by the sound of overhead caving, which proceeded in spite of the fact that the heading was advanced without the use of dynamite but entirely by digging. Breast-boarding was required through much of the operation.

Relative to the materials observed in the "Rise " Drift, the rocks of the collapse block exposed in the Exploratory Drift are compact. This, at least in part, may be attributed to compaction on initial collapse, but it would appear that the high temperature and humidity encountered in this drift may cause a healing effect on these materials. Nevertheless, there is little doubt that somewhere between the Exploratory Drift and the "Raise" Drift the material could be made to flow.

The authors' opinion is that if material were continuously drawn out by mining at the "Raise" Drift level, the rock above would collapse under its own weight and caving would proceed upward to the ground surface. Probably the only conclusive way to evaluate this opinion is through an actual block-caving test. Such caving might be hindered to some extent by jamming of finger raises with massive blocks like the one described in the Exploratory Drift, but otherwise no obstacle is apparent that would seriously hinder a successful block-caving operation.

Three points emerge which could have practical importance from a mining point of view:

In the first place, it is apparent that huge quantities of rock could be removed by block-caving methods from a single draw level (for discussion of these methods and further details of mining conditions encountered and

mining methods used in the driving of the Exploratory and "Raise" Drifts, the reader is referred to a report being prepared by William G. Flangas and L. E. Shaffer[16]). The unstable material as presently outlined above ground zero has been estimated at 600,000 cubic yards. If caving should be continued to the ground surface, this volume would be at least doubled.

Of equal significance from the mining point of view is the fact that, in the gross sense, the caved materials remained intact. If the sought-after ore were distributed in small pockets, as is frequently the case, these could be removed directly to the mill without the necessity of sorting the ore from the worthless country rock as would be necessary if mixing were extensive. Furthermore, pulverization due to collapse may eliminate the necessity of some grinding operations in the milling process.

Another significant fact is that no anomalous radioactivity was encountered in the Rainier "Raise" Drift. In a mining operation, the initial blast could be detonated at the bottom of a winze or incline designed in such a way that re-entry at the level of the main drift would allow complete elimination of radiation as a mining hazard.

In the Neptune area, definition of a central collapse block is complicated to some extent by the initial upward displacement of the domed mass as described in the Introduction and the fact that primary shearing broke through to the surface with expulsion of large amounts of rock materials. Nevertheless, the stratigraphic units as defined can still be recognized from drill core, and in the gross sense the different lithologic types are found to be distributed in an essentially unmixed condition. Certainly, there has been extensive fracturing and a limited amount of mixing is apparent. For example, hard porcellanic rock, typical of the upper and lower parts of TOS_{7-3n}, are commonly found intermixed with materials of the adjacent TOS_{7-4n} and TOS_{7-2n} as if they had been propelled like bullets into the less coherent sandstone (TOS_{7-2n}) and lapilli tuff (TOS_{7-4n}). TOS_{7-4n} is noticeably compressed but still intact. Mixing is observed between subunits TOS_{7-6n} and TOS_{7-7n} and between the upper part of TOS_{7-5n} and TOS_{7-6n}. Such mixing might be expected for at least two reasons. In the first place, large blocks have been heaved to the surface where they are observed as rubble strewn down the mountainside. In the second place, these upper units were not confined by overlying strata during the blast to the extent that the lower units were.

The boundary of the central collapse block to the northwest and southwest of ground zero is fairly definitely fixed by a marked shear zone which is believed to be primarily a collapse feature. However, to the northeast and particularly to the southeast, definition of a boundary is complicated by primary shear and removal of material.

E. The Main Shear Zone

The concept of a main shear zone was first considered during the driving of the Rainier "Raise" Drift. Essentially undisturbed, flat-lying strata were mapped to station 1 + 85 (see Plate V), where they are abruptly terminated by closely spaced, nearly vertical, open fractures as shown in Fig. 9. This breakoff is extended downward by analysis of drilling and core data from G hole.

Between stations 1 + 90 and 2 + 10 in the Rainier "Raise" Drift, only fine pulverized sand with a few coherent blocks up to 1 or 2 feet in diameter were encountered. At this position, the presence of a large (estimated 1100 cubic yards) cavity became apparent after the pouring of large quantities of pulverized rock into the drift. An estimated 80 cubic yards of muck were removed before the cavity could be observed by peering up between the spiling. The cavity was estimated to be about 40 feet high and roughly cylindrical in shape with a 15-foot radius. This pulverized zone extended to about station 2 + 10 where steeply dipping (70°) bedding was measured. Observations, as the heading was advanced, showed that the bedding was progressively flatter until it was 45° over ground zero. The dip is 55° at station 2 + 90 and finally 22° at station 3 + 30 where it is abruptly terminated by the steeply dipping fault shown in Fig. 10. From this point on to station 3 + 58 the rock breakage is characterized by great slabs of rock (3 to 6 feet thick) which are successively displace downward as one progresses toward the center of the collapse block. These massive blocks remained intact and show prominent slickensides on fault surfaces, as shown in Figs. 11 and 12, while adjacent granular materials are sheared to a loose, friable material. It is interesting to note that open fractures, as observed in Figs. 11 and 12, curve and are closed in their extension into the more friable materials. This observation finds explanation in the expected variations in coefficient of internal friction (ϕ angle) in these two rock types.

The closely spaced faults exposed between stations 3 + 47 and 3 + 58 as shown in Fig. 14 are interpreted as shear fractures resulting from a vertical (gravity) principal stress. A stress ellipsoid is included above station 3 + 50 on Plate V in order to illustrate this point.

In Rainier cross section B-B' (Plate VI), material recovered from drill holes I-2 and J-2 is observed to be particularly pulverized between depths 78 and 109 feet in I-2 and depths 55 to 84 feet in J-2. This pulverization is believed to be the result of a concentration of shear slippage in these zones.

As pointed out in previous paragraphs, this zone of pulverization may be, at least in part, attributed to primary (blast) shear stresses. One should expect that these primary stresses should project out from ground zero until the energy is dissipated in the form of heat, massive displacements or shock waves. Relative to the case at point (Rainier), visible effects are described in the discussion of fracturing where it was concluded that the open fractures observed in the "Raise" Drift originated as primary shear fractures that subsequently acted as planes of weakness which favored the collapse of material into the cavity. A thin-section analysis of field oriented samples of rocks adjacent to these fractures should help to verify this hypothesis.

The main shear zone in the Neptune area, as in the Rainier area, is defined on the basis of a particularly pulverized zone encountered in drill holes. This zone is characterized by lack of whole core and by high drill-fluid losses. It should be apparent from preceding discussions of fracturing and collapse that the pulverized zone is due to primary (blast) stresses as well as collapse (gravity) shear. The blast effects were dominant in the southeast direction where the explosion broke through to the surface, while collapse shearing is dominant on the southwest and northwest where the existence of a steep free-face favored shearing by the force of gravity. The shear zone defined on the northeast end of Neptune section A-A' (Plate II) is believed to be a transitional case in which both primary and secondary shear were of importance.

VI. RECOMMENDATIONS FOR FUTURE WORK

Initially it is suggested that the Rainier Event be analyzed in the detail necessary to definitely verify or disprove the hypotheses advanced in this report; and further, that basic criteria be established by which the initial cavity, the crushed zone, the fractured zone, etc., can be most readily defined. Once fundamental hypotheses have been conclusively verified and basic criteria established for their recognition, then short cuts to the analysis of other shots should become evident, at least for those detonations in layered pyroclastic rocks.

Stratigraphic Correlations. Rock distributions as depicted in Plates I through VI should be checked by thin-section analysis. A few of the pertinent correlation which should be checked are as follows:

1. Samples from the jumbled materials on the northeast wall of the Rainier Exploratory Drift at stations 16 + 25 and 17 + 50 should be compared with undisturbed samples of TOS_{7-6r} obtained from drill holes R and G, care being taken to select similar lithologies. According to Warner and Violet[7] "a lineation is visible as a fine fibrous material in plain light and as an oriented birefringence under crossed nicols. Such linear structures have also been observed in the preshot rocks." No mention is made of what preshot rocks, but in any case such a feature should have correlative value.

2. The large block of rock ($TOS_{7-8r\ ?}$) adjacent to the drilling alcove at station 16 + 84 in the Exploratory Drift should be compared with samples of TOS_{7-8r} from the "Raise" Drift.

3. TOS_{7-8r} should be further checked by studying the ten-foot massive unit at its top as observed in drill holes I-2, U-2, R-2, and K, and in the large collapse blocks between stations 3 + 35 and 3 + 45 in the "Raise" Drift. At the same time an effort should be made to establish a precise correlation between undisturbed rock adjacent to the central collapse block at opposite ends of the "Raise" Drift. This may require further drilling above and below the drift in order to encounter correlative sequences.

Additional drilling is certainly needed, particularly northwest of the shot point and above the "Raise" Drift, to more accurately locate other subunit contacts. As the reconnaissance examination progresses, other problems of correlation will become evident and these problems should be worked

out as they are recognized.

The main item that should be kept in mind in selecting specimens for thin-section analysis or for any other measurement is that comparisons should be made at the same stratigraphic horizon. This requisite is imperative, even to different samples taken from the same subunit, since the latter are themselves composed of varied lithologies.

The Initial Cavity. Laboratory melting tests and chemical analysis of specimens (preshot) from rock unit TOS_{7-6r} and adjacent subunits should prove or disprove the suggestion that certain lithologies are particularly susceptible to fusion.

The Crushed Zone. Measurements, on removed samples, of bulk density, grain density, porosity, permeability and compressive strength provide useful empirical data. Additional measurements appear to be warranted.

Fractures in the "Raise" Drift. The postulate that the open fractures at station 1 + 85 and between stations 3 + 30 and 3 + 85 in the Rainier "Raise" Drift (see Figs. 9 through 15) are the result of primary (blast) shear with secondary (collapse) movement perhaps can be studied effectively with thin-sections. Oriented samples of slip surfaces are suggested as a starting point. This study can be expanded to include the joints between stations 1 + 50 and 1 + 55 in the "Raise" Drift as well as the many fractures observed in the Exploratory Drift.

Variations in fracturing due to rock type can probably best be evaluated in situ after definite criteria have been established for the recognition of blast fracturing. Analyses of explosions in rock types other than pyroclastic material will certainly be necessary to arrive at a useful conclusion relative to mining practice.

Tension Fractures. Fractures like those pictured in Fig. 8 of this report should be studied with the purpose of definitely establishing their origin as preshot, blast effect, or drilling effect. A search of the literature is suggested as a starting point since much research has been conducted by various drilling, petroleum, and mining companies relative to rock breakage by core drilling. Thin-section studies of such cracks observed in the Rainier area may also be instructive.

Properties of the Central Collapse Block. The generally incoherent

nature of rock materials in the central collapse block make difficult the application of the standard methods for measurement of porosity, permeability, density, strength, and elastic properties. Experiments could be designed to test the healing effect of high temperature and humidity on pulverized rock materials like those exposed in the Exploratory Drift.

A drop cone might be used as an empirical means of defining the relative hardness of materials, as is done in soil mechanics.

Thin-section comparison of collapse materials with stratigraphically equivalent rocks which have not been disturbed should reveal changes in rock fabric.

More exploration is certainly needed above the "Raise" Drift level to delimit the extent of the central collapse block. The pictorial and descriptive approach as applied in the present report perhaps will be as productive as any. An effort should be made to determine the size and distribution of cavities. Probably the most practical test (to be applied after all other analyses are complete) would be an actual block-caving operation.

Measurement of Strength and Elastic Properties. The strength and elasticity of the test medium is certainly fundamental to evaluating the effects which will result from nuclear detonation. Accurate measurement of these properties is a difficult problem. The scale factor as discussed by Hubbert[11, 12] must be taken into consideration as is the practice in a model study of geologic phenomena. Two important factors of consolation in evaluating nuclear tests are that the time factor is not a problem and that the origin of maximum principal stress is known. Nevertheless, a mountain of rock should be expected to have strength and elastic properties which differ from a small test sample of the same rock, even if discontinuities such as stratification and joints are ignored. The great importance of fluid pressures in determining rock strength has recently been discussed by Hubbert and Rubey.[13]

Static tests under fluid confining pressure is probably an improvement over tests on unconfined specimens. Equation of state measurements allow a degree of dynamic similarity. Perhaps instrumentation could be devised which would measure in situ such properties as fluid pressure, shock, particle velocity, etc., during actual explosions. The results of such measurements, if successful, would certainly be of tremendous significance in the fundamental understanding of explosion effects.

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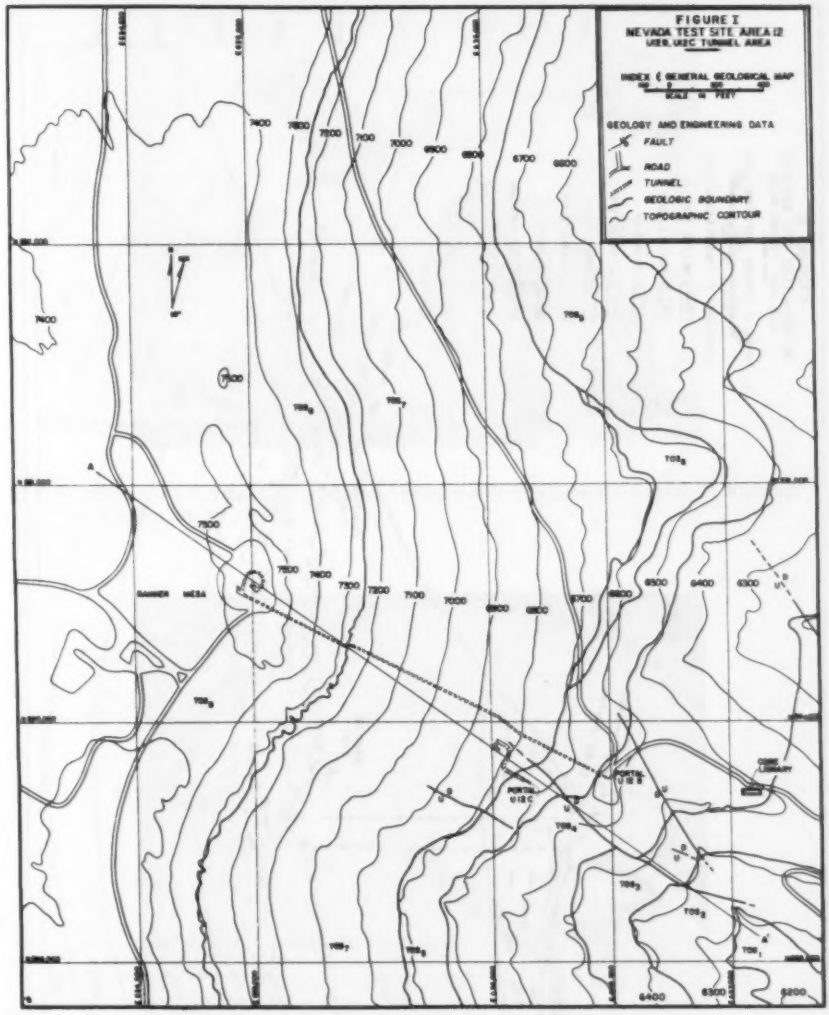

MUL-9185

Fig. 1. Index and general geologic map of the Rainier–Neptune area.

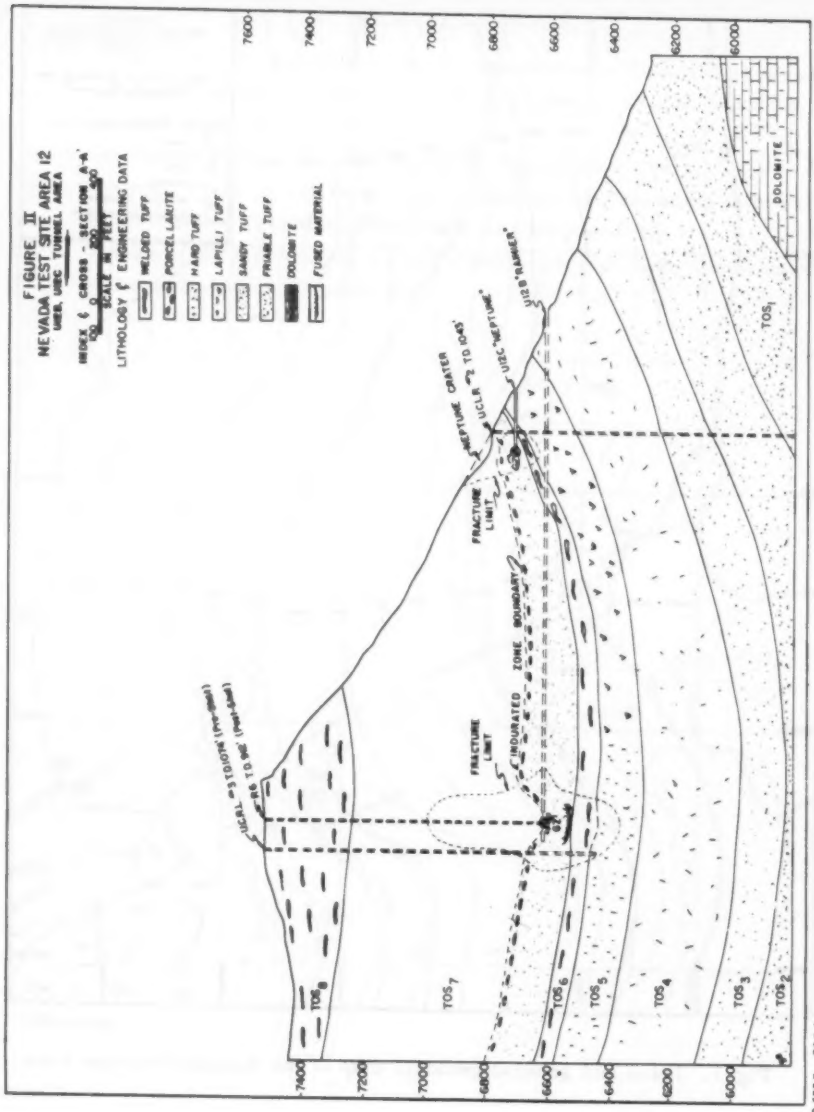

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Fig. 2. Geologic cross section through Rainier and Neptune areas.

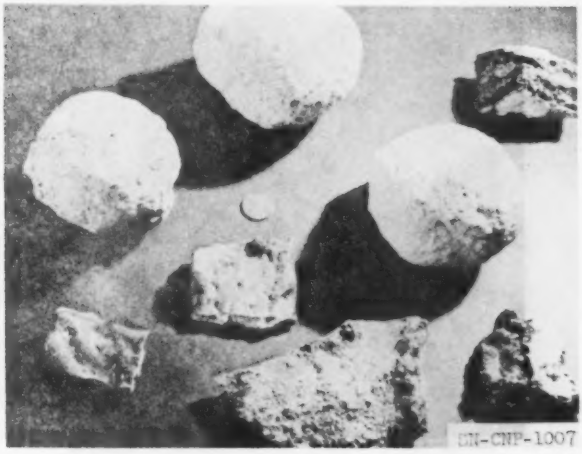

Fig. 3. Rock-ball concretions and fused rock fragments found in Rainier Exploratory Drift.

Fig. 4. Fused material in U12-B Exploratory Drift.

Fig. 2. Geologic cross section through Rainier and Neptune areas.

MUL-9186

Fig. 5. Collapsed TOS_{7-7r} showing shear plane in U12-B Exploratory Drift.

Fig. 6. Pulverized rock (TOS_{7-7r}) in central collapse block U12-B Exploratory Drift.

Fig. 7. Stringer of fused rock and adjacent crushed TOS_{7-6r} (right) and collapsed TOS_{7-7r} (left) at station 16+25 in U12-B Exploratory Drift.

Fig. 8. Primary (blast) tension fractures in core from U12-B Rainier hole H.

Fig. 9. Limit of Rainier collapse zone showing near vertical fractures with slight gravity displacement at station 1+85 in "Raise" Drift.

Fig. 10. Loose volcanic gravel in fault contact with sheared blocks of massive lapilli tuff on the southwest wall of U12-B "Raise" Drift at station 3+34.

Fig. 11. U12-B "Raise" Drift at station 3+35 showing vertical slickensides on heading block of massive tuff and open fractures (Strike N-10°-E) in downdrop fault block.

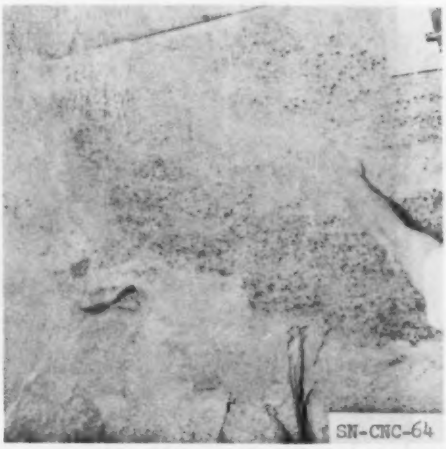

Fig. 12. U12-B "Raise" Drift (station 3+31 to 3+35). Open fractures in the massive lapilli tuff (TOS_{7-8r}) are closed and curved on projection through the loose pebbly tuff (TOS_{7-9r}).

Fig. 13. Pebbly volcanic tuff showing a horst bounded by normal (gravity) faults on northeast wall of U12-B "Raise" Drift at station 3+65.

Fig. 14. Secondary (gravity) faults are illustrated by displaced stratigraphic contact between brown tuffaceous sandstone below and white sandy tuff above. (Northeast wall between stations 3+50 and 3+55 in U12-B "Raise" Drift.)

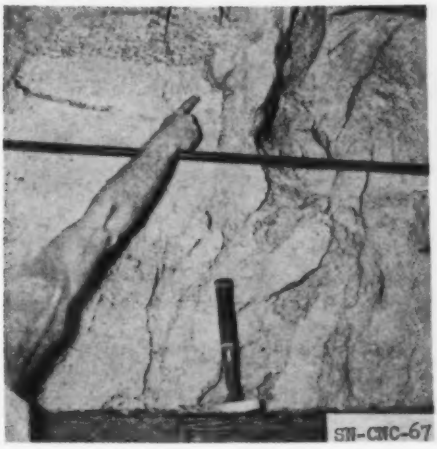

Fig. 15. Vertical fault shown by down-dropped massive brown tuff adjacent to bedded white tuff. (U12-B "Raise" Drift at station 3+47.)

Fig. 16. Heading at station 3+48 in U12-B "Raise" Drift. Note the displacement of the lapilli tuff bed.

Fig. 17. Slump structures in bedded tuff of Rainier central collapse block at heading station 2+55 in U12-B "Raise" Drift.

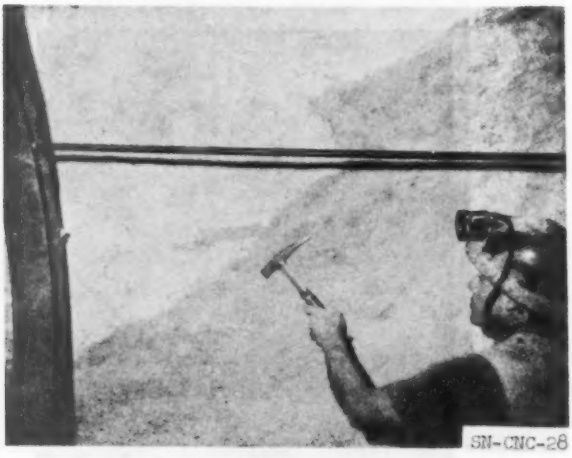

Fig. 18. Slump structures in bedded tuff of Rainier central collapse block between stations 2+50 and 2+55 along the northeast wall of U12-B "Raise" Drift.

Fig. 19. Undisturbed rock at U12-B "Raise" Drift heading station 3+76.

Fig. 20. Cavity probe operation over station 3+20 in U12-B "Raise" Drift.

Fig. 21. Surface fracture adjacent to cliff face above U12-B Rainier detonation point. (See Fig. 23 for location.)

Fig. 22. Surface fracture adjacent to cliff face above U12-B Rainier detonation point. (See Fig. 23 for location.)

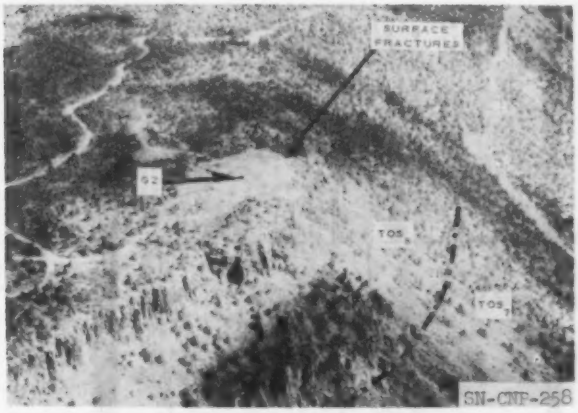

Fig. 23. Aerial photo of Rainier Mesa above U12-B Rainier shot point showing location of fractures illustrated in Figs. 21 and 22.

Fig. 24. Surface rubble below Neptune crater.

Fig. 25. Fractured welded tuff (TOS_6) overlying undisturbed lapilli tuff (TOS_5) at station 0+40 in U12-C Neptune Exploratory Drift.

Fig. 26. Blast mixed lithologies TOS_{7-2n} and TOS_{7-3n} at station 0+96 in U12-C Neptune Exploratory Drift.

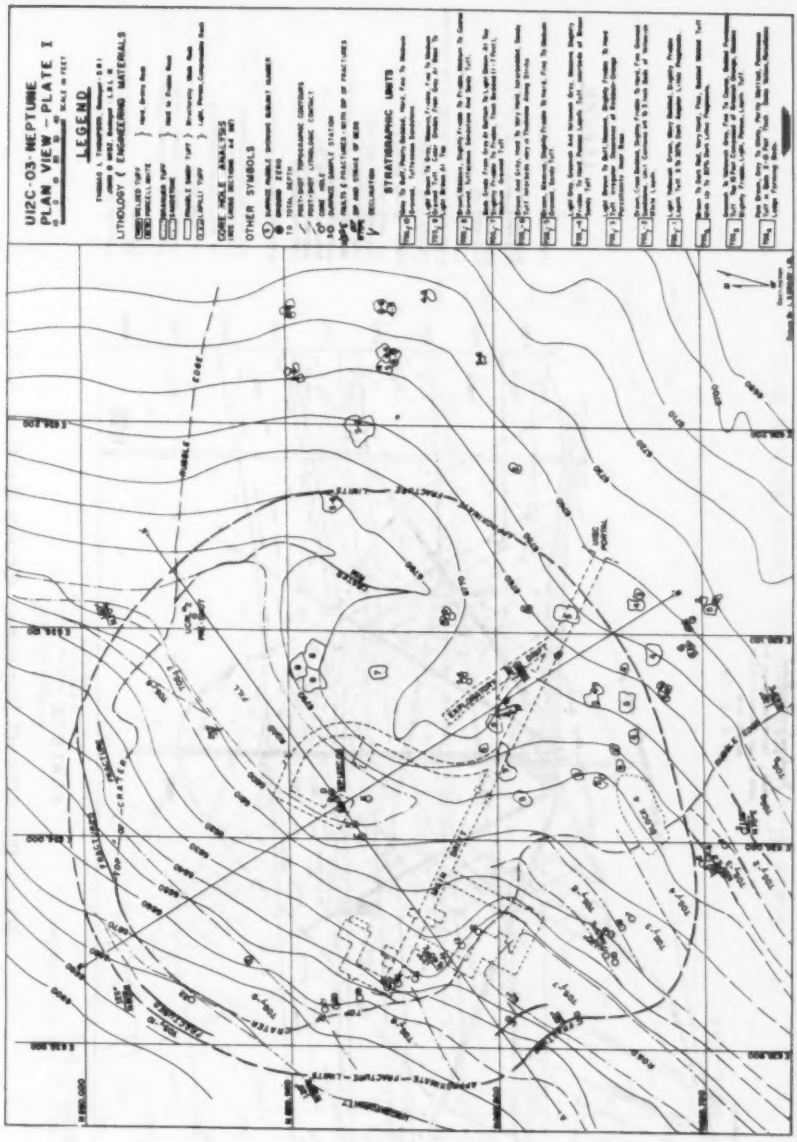

Plate I. U12-C Neptune Plan.

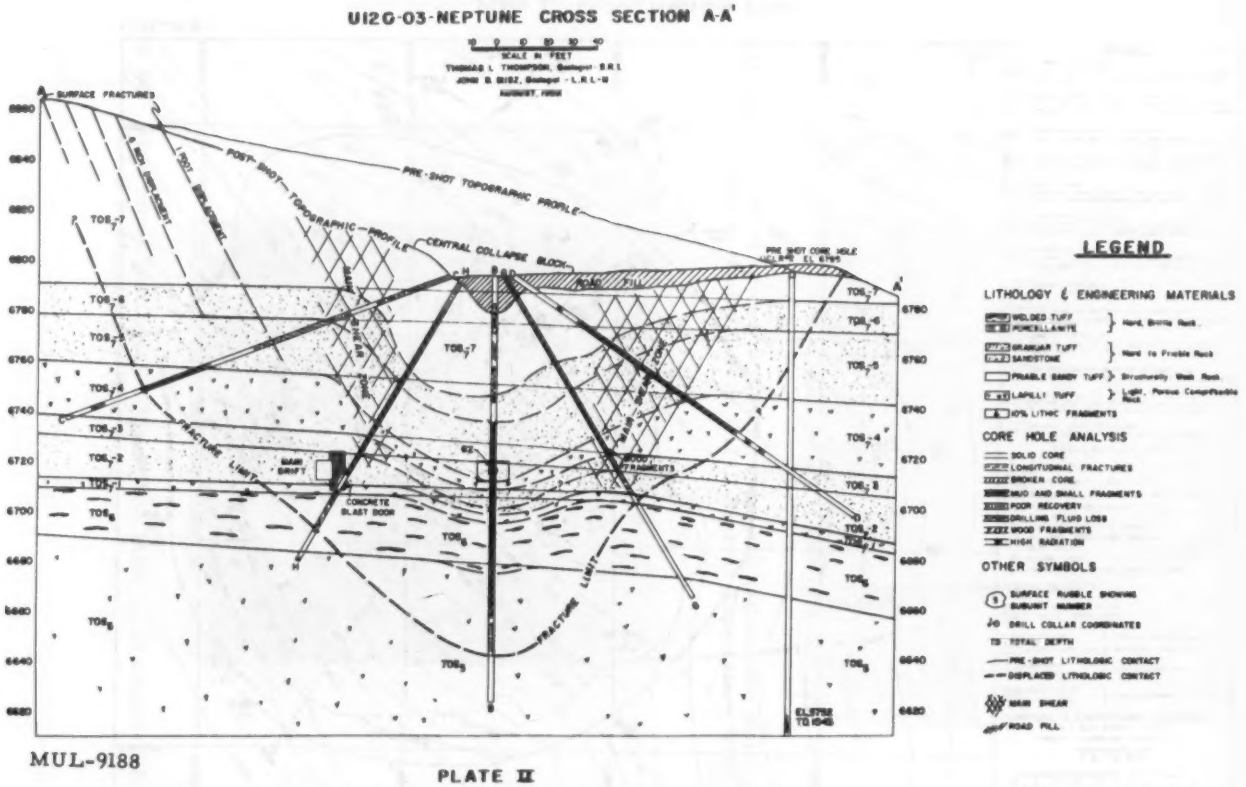

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PLATE II

Plate II. U12-C Neptune, Cross Section A-A'.

Plate II. U12-C Neptune, Cross Section A-A'.

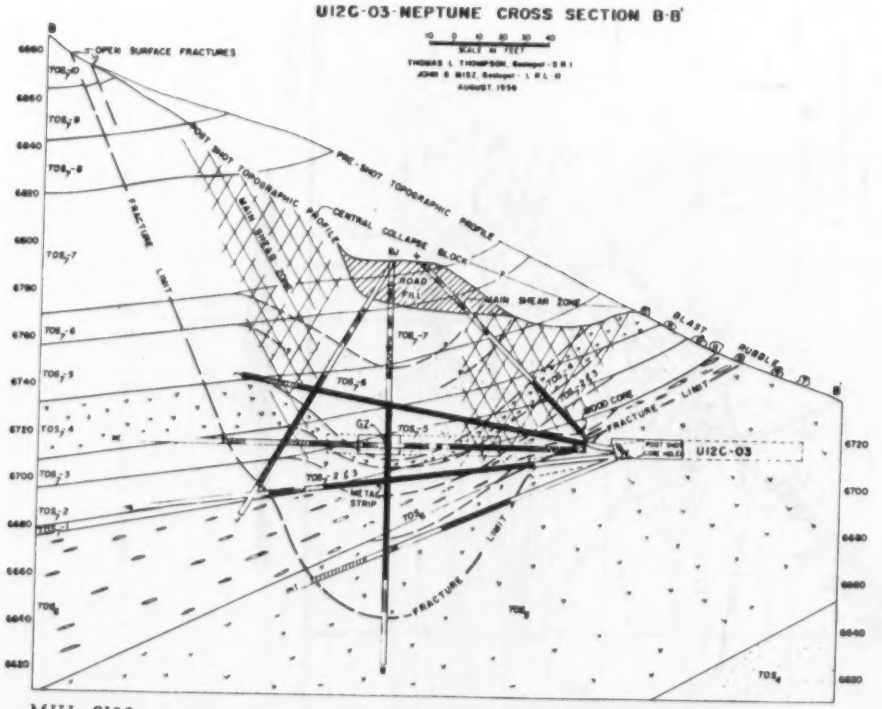
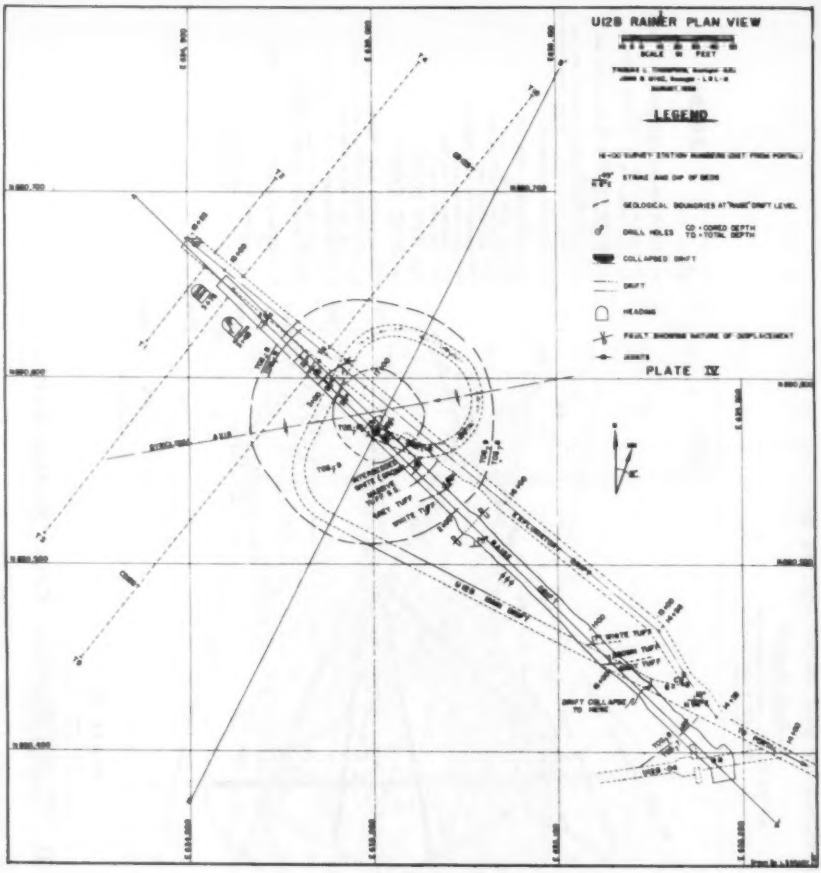


Plate III. U12-C Neptune, Cross Section B-B'.



MUL-9190

Plate IV. U12-B Rainier Plan.

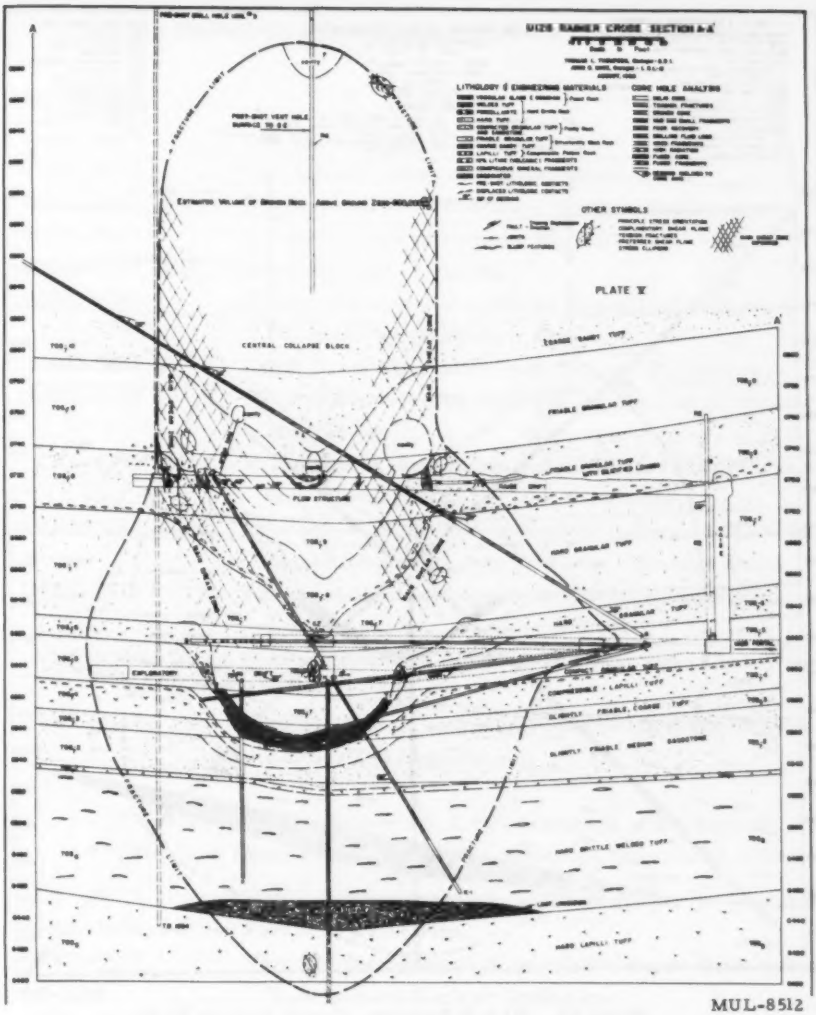


Plate V. U12-B Rainier, Cross Section A-A'.

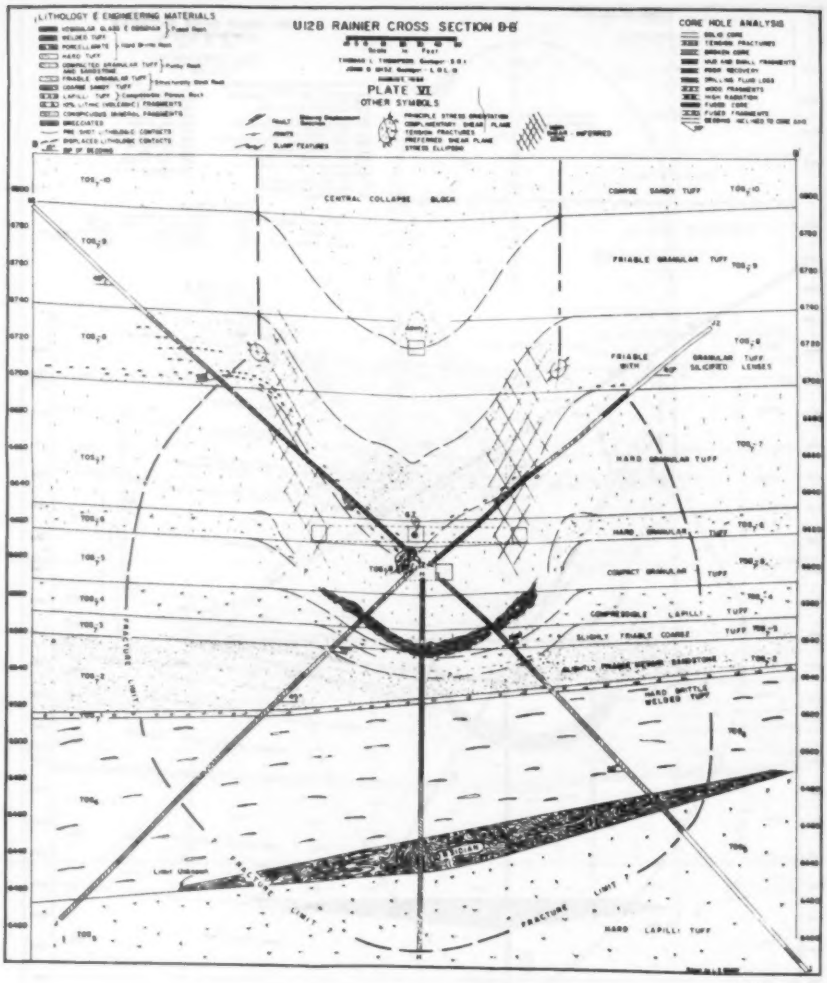


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Plate VI. U12-B Rainier, Cross Section B-B'.

LIST OF PREVIOUS PLOWSHARE AND/OR RELATED REPORTS

Report No.	Title
UCRL-4659	Deep Underground Test Shots.
UCRL-5026	Non-Military Uses of Nuclear Explosions.
UCRL-5124, Rev.I	Phenomenology of Contained Nuclear Explosions.
UCRL-5253	Industrial Uses of Nuclear Explosives.
UCRL-5257, Rev.	Peaceful Uses of Fusion.
UCRL-5281	Temperatures and Pressures Associated with the Cavity Produced by the Rainier Event.
UCRL-5457	Large Scale Excavation with Nuclear Explosives.
UCRL-5458	Mineral Resource Development by the Use of Nuclear Explosives.
UCRL-5538	Evaluation of the Ground Water Contamination Hazard from Underground Nuclear Explosions.
UCRL-5542, Rev.	Properties of the Environment of Underground Nuclear Detonations at Nevada Test Site. Rainier Event.
UCRL-5623	Radioactivity Associated with Underground Nuclear Explosions.
UCRL-5709	Hydroclimatology and Surface Hydrology of San Clemente Island.
UCRL-5757	Geologic Studies of Underground Nuclear Explosions Rainier and Neptune

* * *

Plowshare Series: Report No. 2. Proceedings of the Second Plowshare Symposium (Held at San Francisco May 13-15, 1959):

UCRL-5675	Part I : Phenomenology of Underground Nuclear Explosions
UCRL-5676	Part II : Excavation.
UCRL-5677	Part III: Recovery of Power and Isotopes from Contained Underground Nuclear Explosions.
UCRL-5678	Part IV: Industrial Uses of Nuclear Explosives in the Fields of Water Resources, Mining, Chemical Production, and Petroleum Recovery.
UCRL-5679	Part V : Scientific Applications of Nuclear Explosives in the Fields of Nuclear Physics, Seismology, Meteorology and Space.

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APPENDIX 9

PART I

DESCRIPTION OF THE COWBOY SEISMIC RECORDS
(Attached are examples of these records)

The seismic records are a plot of the amplitude of the velocity of the seismic wave as it passes a detector versus time. The time scale is the vertical lines on the bottom and top of the record. Each space equals 0.010 seconds (every fifth line accented). Seismic stations were located 14,400 feet (station 4), 22,100 feet (station 5), and 44,600 feet (station 6) from the place of detonation in the salt mine. At each station there were six seismic detectors, 200 feet apart, located along a line pointed in the direction of the mine. Each detector is separately recorded at low magnification (the bottom 6 seismic traces) at an intermediate magnification (the middle 6 seismic traces) and at a very high magnification (only 3 traces shown). For illustrative purposes there is no need to show more than one magnification and the intermediate one is most understandable.

The magnification (or electronic amplification) used depended upon the distance, the expected signal strength, and the noise level existing at the station at the time of the shot. The magnifications shown are relative magnifications. To obtain a measure of the decoupling or muffling one calculates as follows

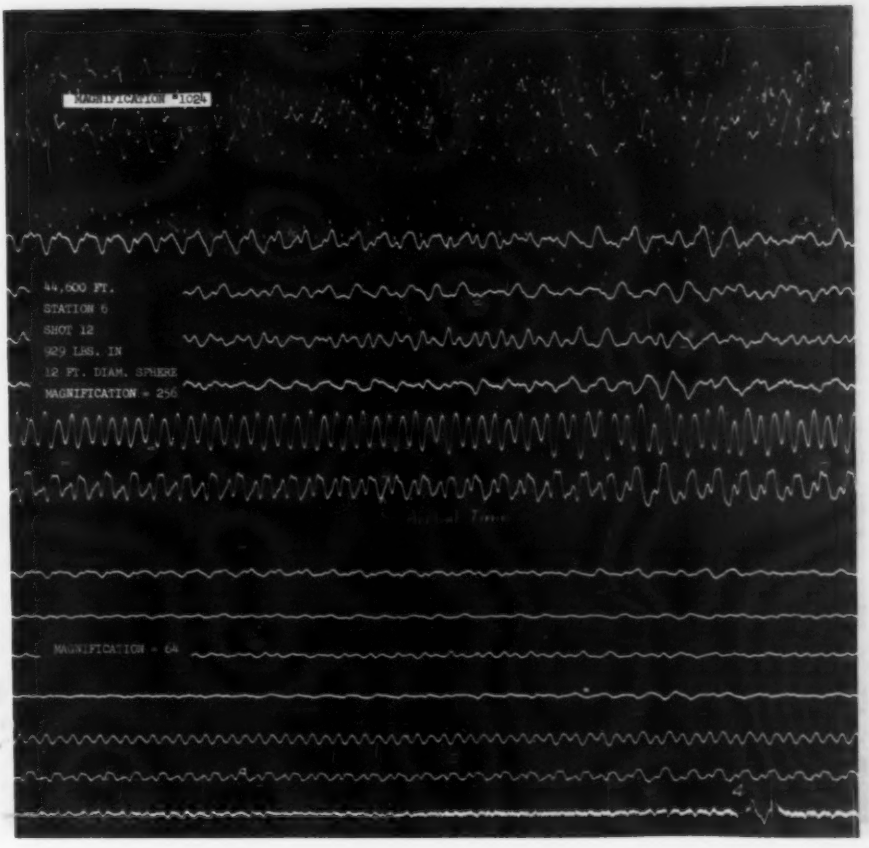
$$\frac{\text{(Amplitude of wave on the tamped shot)}\ /\ \text{(Relative Magnification of the tamped shot)}}{\text{(Amplitude of the same wave on the sphere shot)}\ /\ \text{(Relative Magnification of the sphere shot)}}$$

This quantity represents the amount a seismic wave can be reduced by placing the source in a hole. Using this formula, the 929 pound charge in the 12 foot diameter sphere yields a decoupling of about 25. The 954 pound charge in the 30 foot diameter sphere gives a decoupling of about 120. These factors are a measure of the decoupling of an HE charge in a large hole in salt compared to an HE charge closely tamped in salt. The decoupling theory discussed at the Geneva

Conference on the Discontinuance of Nuclear Weapons Tests compared a nuclear shot in a large cavity in salt to a nuclear shot tamped in tuff, which is now thought to have a coupling larger than a shot tamped in salt by about 2. The decoupling factor of 25 mentioned above was achieved with an HE charge in a hole (in salt) whose volume was only about 1/5 the volume per unit yield required for elastic behavior (full decoupling) in the case of a nuclear explosion. The very much larger pressure spike associated with a chemical explosive charge means that the elasticity condition was violated by a factor of 15 rather than 5 for the 929 pound charge in the 12 foot hole. This may mean that, for nuclear shots, cavities of less than 1/10 the volume required for elasticity would decouple by a factor of 25 relative to close coupling in salt (corresponding probably to a factor of 50 or more relative to "coupled" in tuff).

Another measure of the decoupling is illustrated at station 6. The signal from the shot in the small sphere was so weak that it barely showed in the background noise level. The signal did not show at all above the background or the large sphere shot. The records have been labeled to indicate the expected time of arrival. The background noise level was slightly different on the two days the shots were made. The seismic signals are weaker at station 6 than at other stations because that station is farthest out and waves are weakened by geometrical spreading and because as waves propagate their energy is scattered and absorbed by the earth.

The Cowboy program was under technical direction of the Lawrence Radiation Laboratory. The United States Coast and Geodetic Survey supervised the field seismic program. These records were made under subcontract with the National Geophysical Company.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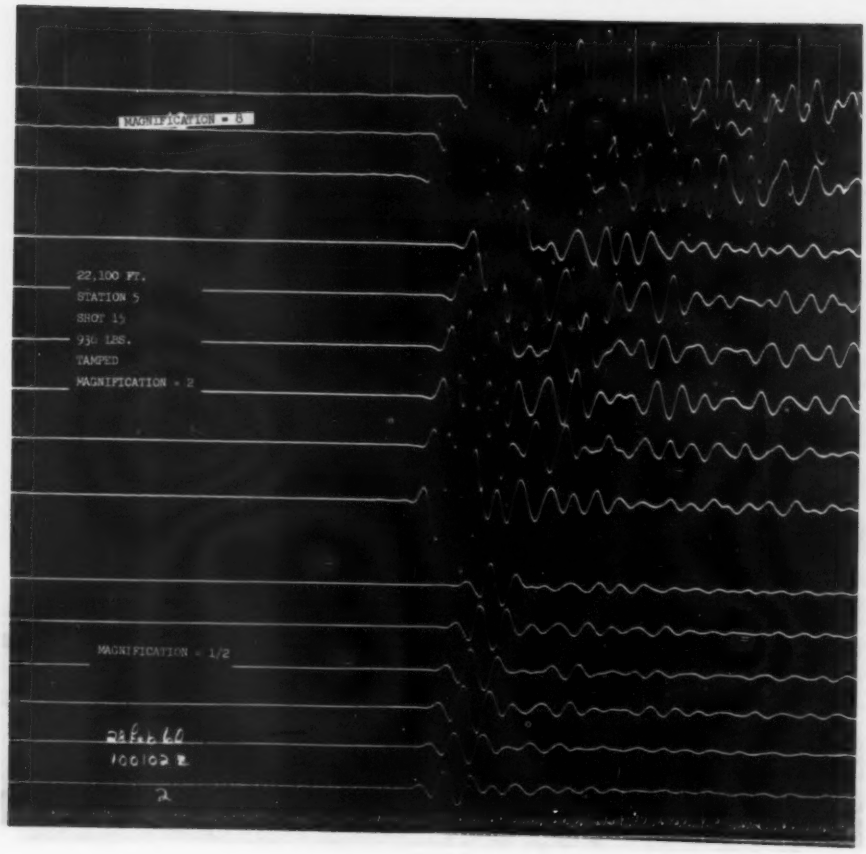
MAGNIFICATION = 64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SHOT 15
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TAMPED
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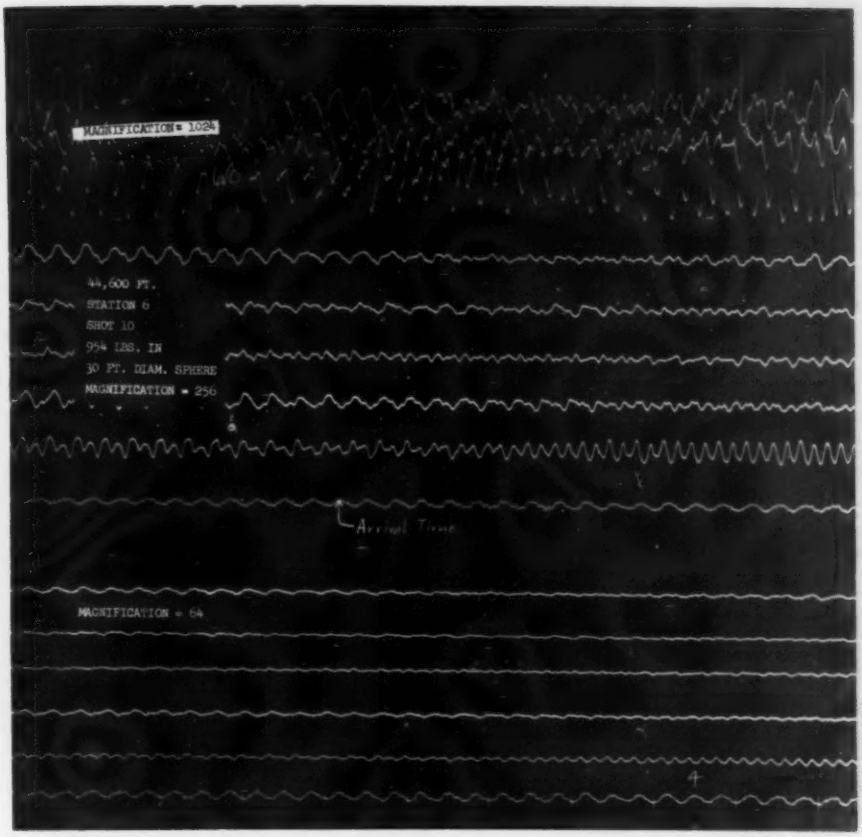
MAGNIFICATION = 1/2
28 Feb 60
100102 Z
2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STATION 6
SHOT 10
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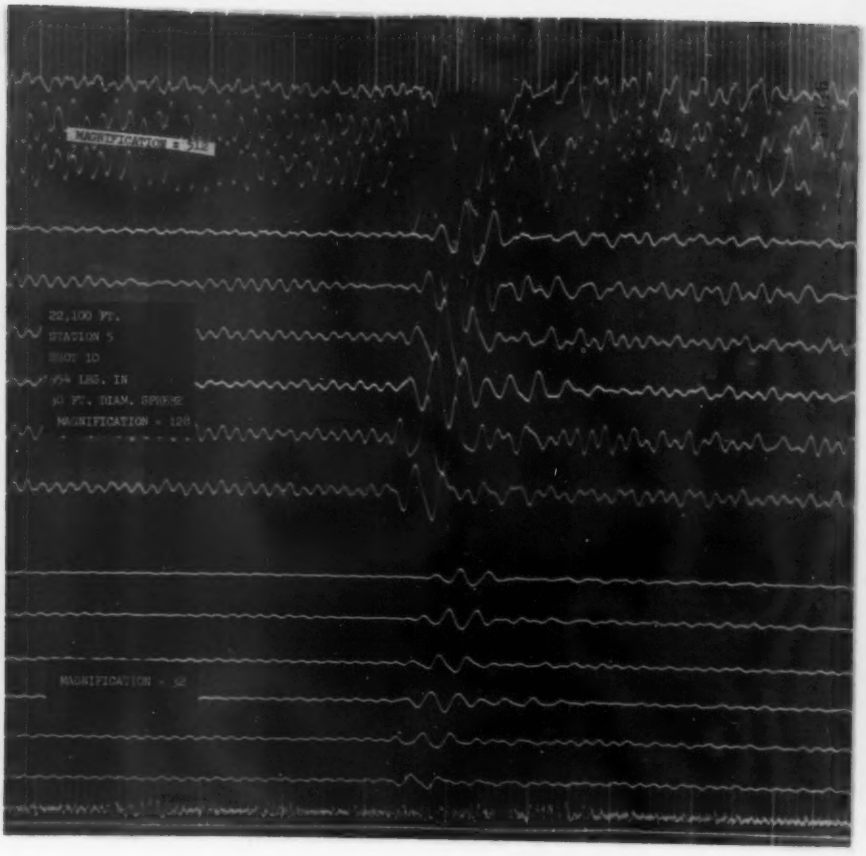
MAGNIFICATION = 256
Arrival Time
MAGNIFICATION = 64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STATION 5
SHOT 10
954 LBS. IN
30 FT. DIAM. SPHERE
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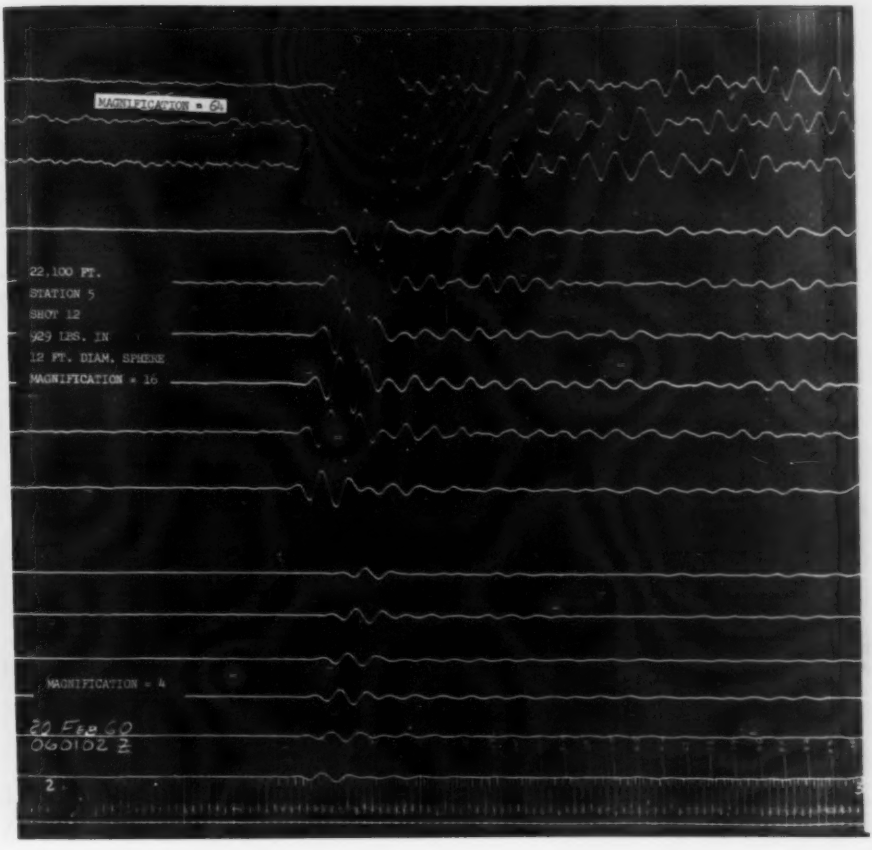
MAGNIFICATION = 32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SHOT 12
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12 FT. DIAM. SPHERE
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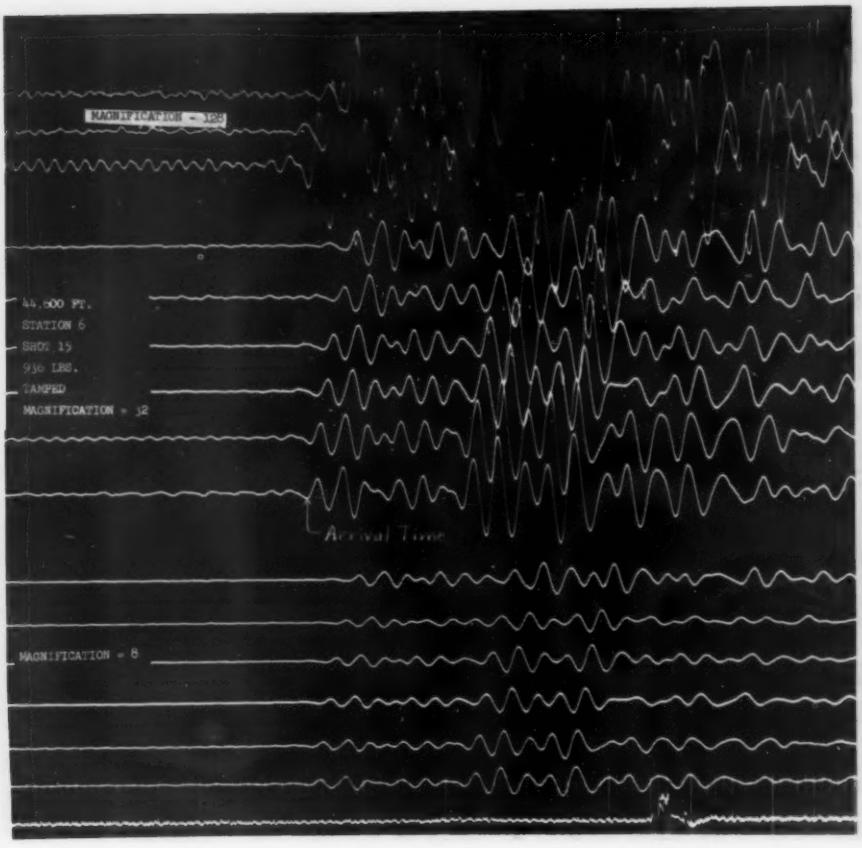
MAGNIFICATION = 4
20 Feb 60
060152 2
2
5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Arrival Time
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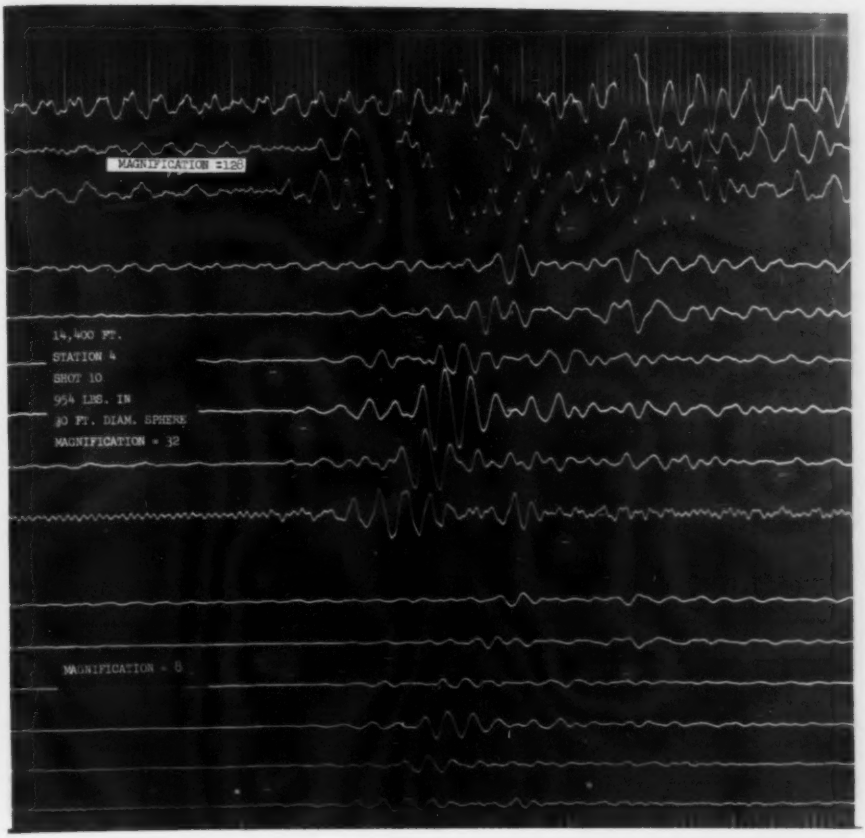
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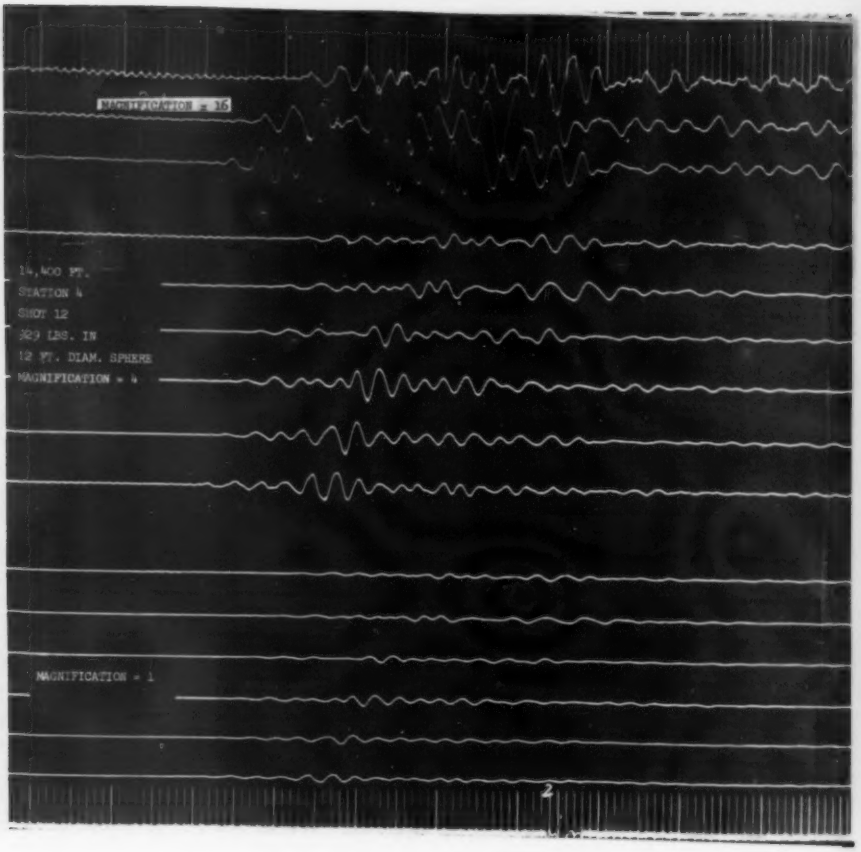
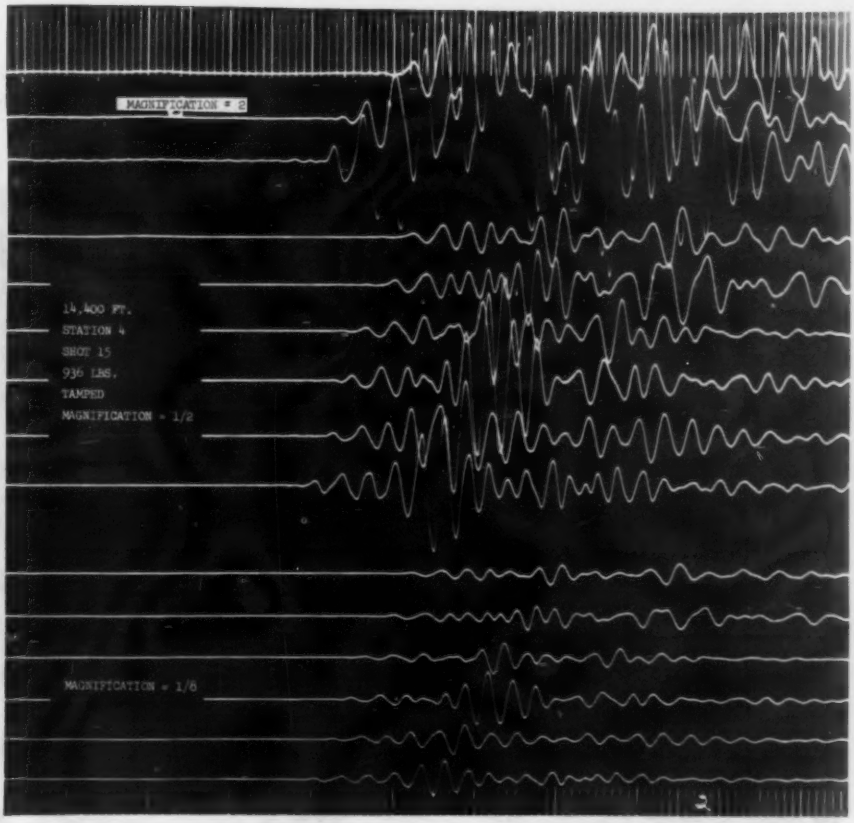
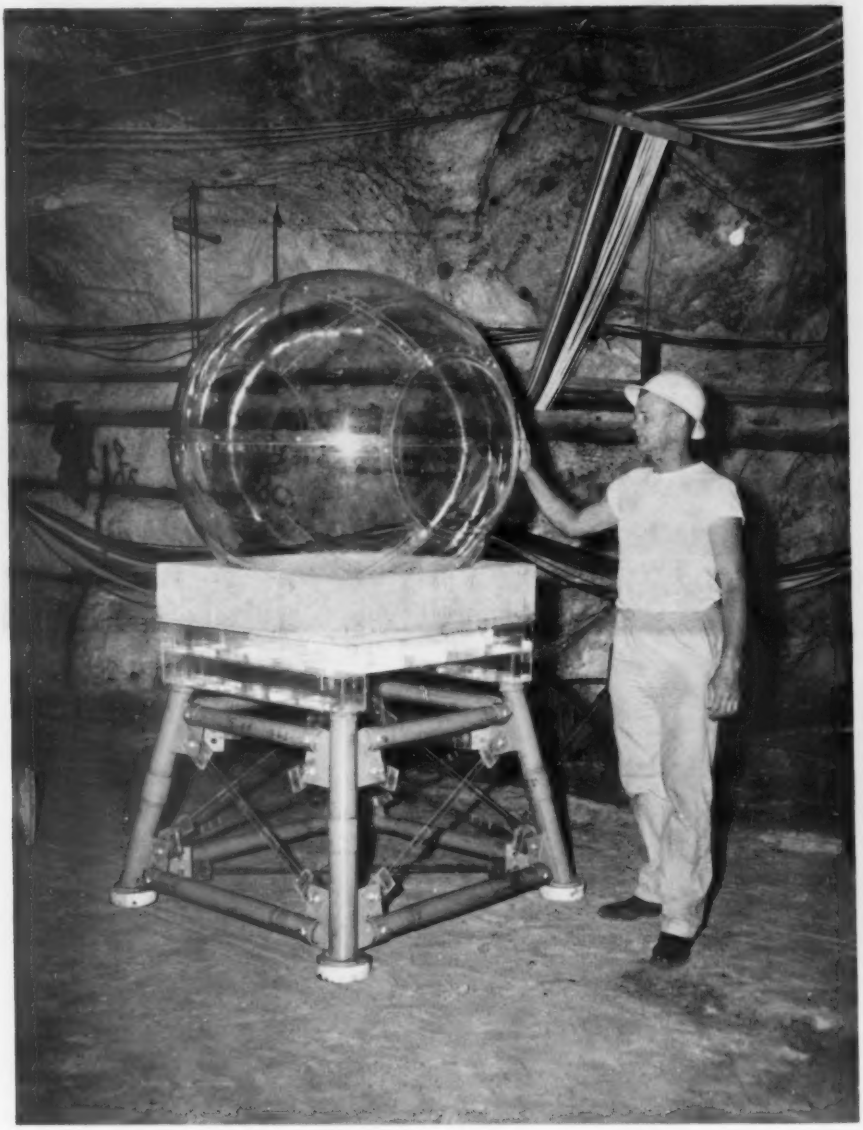
14,400 FT.
STATION 4
SHOT 10
994 LBS. IN
30 FT. DIAM. SPHERE
MAGNIFICATION = 32
MAGNIFICATION = 8


14,400 FT.
STATION 4
SHOT 12
329 LBS. IN
12 FT. DIAM. SPHERE
MAGNIFICATION = 4
MAGNIFICATION = 1
2


MAGNIFICATION = 2
14,400 FT.
STATION 4
SHOT 15
936 LBS.
TAMPED
MAGNIFICATION = 1/2
MAGNIFICATION = 1/6

Part II

The following photographs depict various phases of the cowboy operation conducted by the Lawrence Radiation Laboratory in the Carey Salt Mine near Winfield, La.



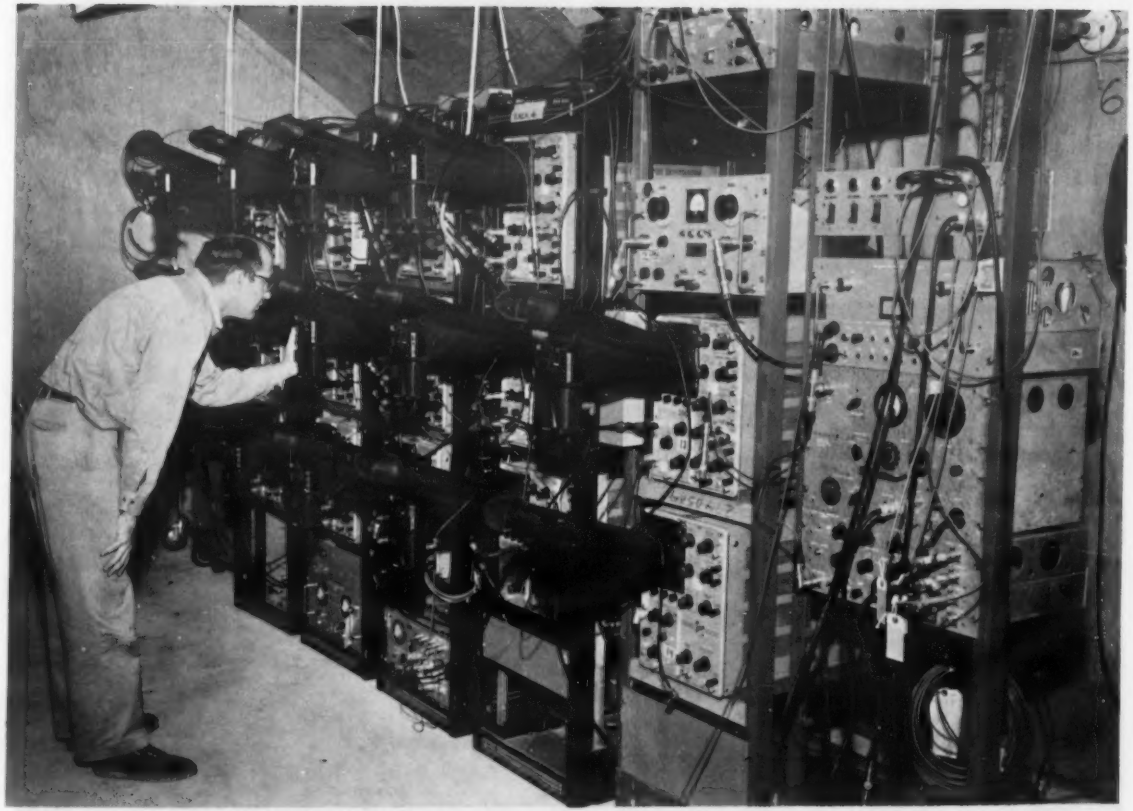
48-inch lucite sphere for 2,000-pound shot on test stand prior to assembly in the cavity. Stand is of polyvinyl chloride plastic topped with a lucite and styrofoam support for the sphere. Sphere was constructed in segments to permit assembly in the cavity since the entry port was too small. Cabling and piping in background is part of the instrumentation for the tests.

Shows typical drift in Carey Salt Mine. Stakes indicate locations of instrument holes for U.S. Bureau Mines test program. Grid lines on walls were painted as part of scientific program.

View in the vicinity of entrance drift to 12-foot-diameter sphere. Front-end loader (left) was used in excavating salt after blasting. Duct work (top and right) for ventilation. Large circular plug (center left) was one of the two utilized in securing access hole to the cavity. Piping and cabling was part of the instrumentation.

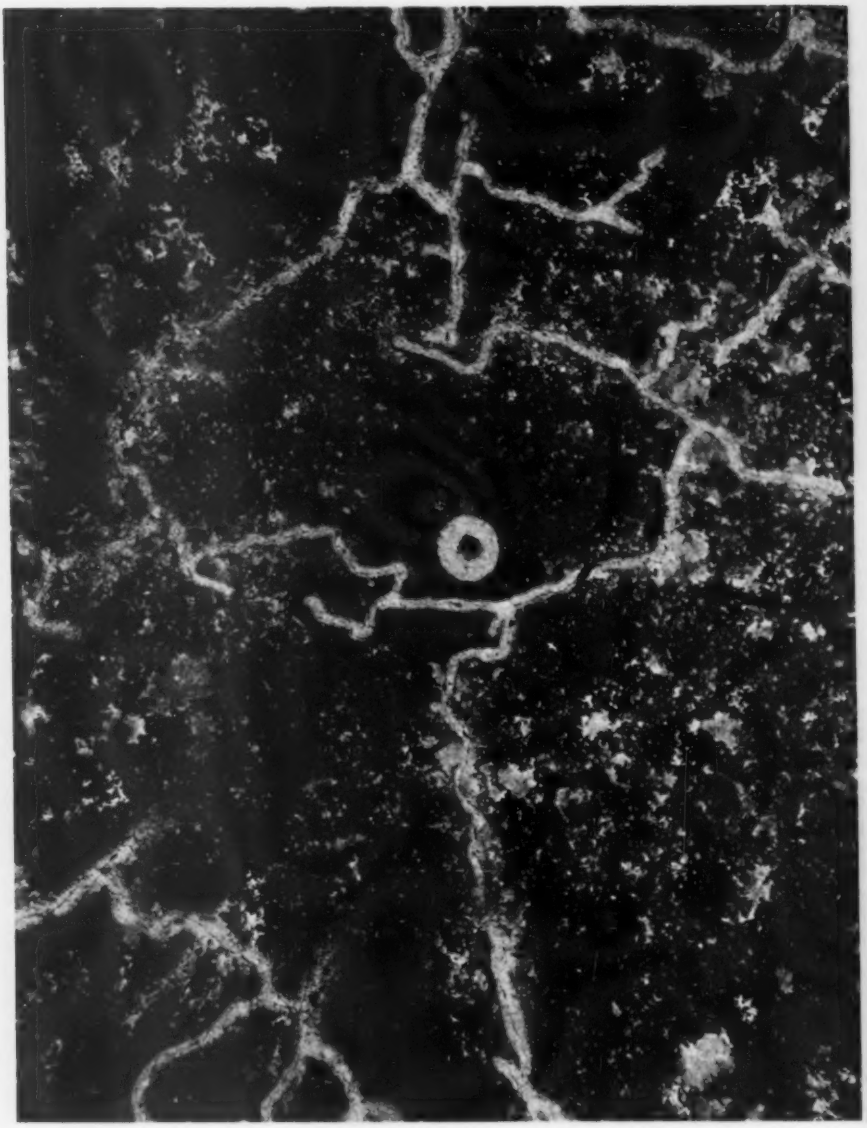
left) was one of the two utilized in securing access hole to the cavity. Piping and cabling was part of the instrumentation.

General view of Carey salt-processing mill (right). Mine shaft and tipple house at left.



Array of electronic recording instruments in bunker approximately 1,600 feet from detonation area. Cameras mounted on the front of oscilloscopes recorded impulses from instruments placed in the immediate vicinity of the test detonations.

View into 12-foot-diameter sphere showing 48-inch-diameter lucite explosive container in place.



View of part of interior of the 12-foot-diameter sphere after a 2,000-pound high-explosive shot. Cracks were painted to accentuate their visibility. The picture was taken from the floor looking up at the top of the sphere.

Vicinity of 1,000-pound H.E. shot buried 110 feet in the floor, after the shot. Explosive was placed in a cylindrical cavity directly below the small wood sign at the center left. Dark patch on roof is residue of vented shot gases which came up a ½-inch steel pipe that was grouted (cemented) into the shot chamber prior to detonation. No surface damage was visible. Cables lead to instruments buried at various distances from the shot.